PB 216 716

THERMAL POLLUTION: STATUS OF THE ART

Frank L. Parker, et al

National Center for Research and Training in
the Hydrologic and Hydraulic Aspects of Water
Pollution Control
Nashville, Tennessee

December 1969

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 216 716

THERMAL POLLUTION:
STATUS OF THE ART

FRANK L. PARKER

PETER A. KRENKEL

National Center For Research and Training in the
Hydrologic and Hydraulic Aspects of Water Pollution Control

REPORT NUMBER 3

Department of Environmental and Water Resources Engineering

Vanderbilt University

School of Engineering

Nashville, Tennessee

December, 1969

[redacted]

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22131

432

THERMAL POLLUTION:
STATUS OF THE ART

FRANK L. PARKER

PETER A. KRENKEL

National Center For Research and Training in the
Hydrologic and Hydraulic Aspects of Water Pollution Control

REPORT NUMBER 3

Department of Environmental and Water Resources Engineering

Vanderbilt University

School of Engineering

Nashville, Tennessee

December, 1969

[redacted]

THERMAL POLLUTION

STATUS OF THE ART REPORT

BY

FRANK L. PARKER

and

PETER A. KRENKEL

VANDERBILT UNIVERSITY

NASHVILLE, TENNESSEE

With assistance on chapters on Mechanisms of Heated Water Discharges and Modeling of Heated Discharges by Dr. Barry A. Benedict and chapter on Mechanisms of Heated Water Discharges by Dr. Edward L. Thackston and chapter on Effects of Temperature on Aquatic Organisms by Dr. George W. Malaney and James N. Speakman, all of Vanderbilt University. A chapter on Effects of Temperature on Pacific Salmon was written by a member of the Pacific Northwest Water Laboratory, Federal Water Pollution Control Administration, Gerald Schuytema.

Prepared for the

Federal Water Pollution Control Administration

Under Grant No. WP-01387-01

December, 1969

ACKNOWLEDGEMENTS

The work described herein was supported by the Federal Water Pollution Control Administration under Research Grant #WP-01387-01. The authors would like to acknowledge the cooperation, aid and understanding of Messrs. William A. Cawley, Frank H. Rainwater, and Joel Fisher all of the Federal Water Pollution Control Administration. The authors would also like to acknowledge the assistance of their colleagues, Drs. Barry A. Benedict, George W. Malaney, and Edward L. Thackston, and Mr. James N. Speakman. The assistance of Mr. Larry Elliott in manifold ways is gratefully acknowledged. Without the typing of the many drafts by Mmes. Peggie Bush, Beverly Laird, and Judy Smith and the art work of Mrs. Vita Rietveld, this report would not yet be finished.

TABLE OF CONTENTS

Page

CHAPTER I Introduction

A. Central Electricity Generating Stations. 3

B. Cooling Water Requirements 12

C. Improving Efficiency of Central Station Steam Electricity Generation 14

D. Alternative Methods of Central Station Energy Production 18

E. Alternative Methods of Heat Dissipation. 21

F. Research Required for Alternate Means of Electricity Generation 21

Bibliography 23

CHAPTER II Physical, Biological and Chemical Effects on Water Quality

A. Physical 1

B. Biological 7

C. Chemical 12

D. Research Needs 13

Bibliography 15

CHAPTER III Effects of Temperature on Aquatic Organisms

A. Known Effects of Temperature 2

B. Recorded Thermal Fish Kills. 19

C. Protective Responses in Aquatic Organisms. 21

Preceding page blank

TABLE OF CONTENTS (cont.) Page

D. Heat Tolerance in Organisms. 24

E. Acclimation of Organisms 26

F. Temperature Selection. 31

G. Thermal Pollution and Dissolved Oxygen Content of Water 35

H. Oxygen Requirements of Fish and Other Aquatic Animals. 35

I. Natural Fluctuations in the Dissolved Oxygen of Water 37

J. Dissolved Oxygen Changes Caused by Discharge of Heated Effluents - Changes During Passage Through the Condensers 37

K. Changes in River and Lake Water Below Heated Discharge Outfall. 39

L. Natural Fluctuations in Temperature. 42

M. Artificial Fluctuations in Temperature 43

N. Effect of Elevated Temperature Upon Biological Populations of Rivers. 44

O. Effect Upon Entrained Organisms. 44

P. Effect Upon Periphyton 45

Q. Effect on Benthos. 46

R. Effect on Aquatic Plants 48

S. Effect on Fishes 49

T. Effect of Elevated Temperature Upon Biological Populations of Lakes 50

U. National Technical Advisory Committee on Water Quality Criteria Recommendations 52

TABLE OF CONTENTS (cont.) Page

V. State Temperature Standards. 56

W. Research Needs 62

Bibliography 65

CHAPTER IV Effects of Heated Discharges on Water Quality and Assimilation

A. Stratification in Impounded Waters 1

B. Effects of Stratified Flow on Water Quality. 10

C. Waste Assimilative Capacity. 11

D. Research Needs 22

Bibliography 23

CHAPTER V Beneficial Effects of Heat Additions

A. District Heating 1

B. Increased Biological Production. 1

C. Control of Marine Fouling. 3

D. Water Works Treatment. 4

E. Waste Treatment. 4

F. Irrigation 5

G. Ice Free Shipping Lanes. 5

H. Water and Sediment Discharge 5

I. Water Supply Source. 7

J. Research Required. 8

Bibliography 10

TABLE OF CONTENTS (cont.)

Page

CHAPTER VI Prediction of Heat Dissipation

A. The Energy Balance 1
B. Heat Dissipation From Reservoirs and Lakes 12
C. Heat Dissipation From Rivers 19
D. Equilibrium Temperature. 34
E. Remote Sensing of Thermal Pollution. 39
F. Research Needs 40
Bibliography 45

CHAPTER VII Mechanisms of Heated Water Discharges

A. Formation and Description of Warm Water Wedges 3
B. Mixing of Heated Waters by Momentum Jets 18
C. Dispersion of Heated Discharges. 42
D. Research Needs 68
Bibliography 73

CHAPTER VIII Modeling of Heated Discharges

A. Stages of Stratified Flows 1
B. Distortion in Heated Discharge Models. 8
C. Physical Requirements of Models. 11
D. Research Needs for Modeling. 13
Bibliography 15

CHAPTER IX Cooling Ponds and Run of the River Cooling

A. Cooling Ponds. 1

TABLE OF CONTENTS (cont.) Page

B. Run of the River Cooling 5

C. Research Required. 6

Bibliography 8

CHAPTER X Cooling Towers

A. Major Sources of Information 1

B. Definitions. 2

C. Atmospheric Towers 5

D. Mechanical Draft Wet Cooling Towers. 5

E. Natural Draft Wet Cooling Towers 11

F. Natural Draft Wet Cooling Towers Theory. 13

G. New Designs for Cooling Towers 15

H. Dry Cooling Towers 16

I. Dry Cooling Tower Theory 17

J. Research Needs 19

Bibliography 21

CHAPTER XI Cooling Tower Problems

A. Climatic Effects of Cooling Towers 1

B. Fog and Plumes From Wet Cooling Towers 1

C. Noise. 6

D. Chemical Wastes From Cooling Towers. 8

E. Water Quality Effects of Cooling Towers. 11

F. Discharge of Condenser Cooling Waters to the Ground. . . 12

TABLE OF CONTENTS (cont.) Page

G. Tower Failures 13
H. Research Required. 14
Bibliography 16

CHAPTER XII Comparison of Cooling Methods

A. Climatic Requirements. 1
B. Cooling Tower Operation. 2
C. Economic Comparison of Cooling Towers. 4
D. Conclusions. 10
E. Research Required. 12
Bibliography 13

APPENDIX A - Literature Review - Effects of Temperature on Pacific Salmon

Pacific Salmon - *Oncorhynchus*. 2
Sockeye Salmon - *Oncorhynchus nerka* (Walbaum). 10
Chinook Salmon - *Oncorhynchus tshawytsha* (Walbaum) . . 19
Coho Salmon - *Oncorhynchus kisutch* (Walbaum) 29
Pink Salmon - *Oncorhynchus garbuscha* (Walbaum) 34
Chum Salmon - *Oncorhynchus keta* (Walbaum). 38
Research Needs 41
Federal Government Sponsored Research. 44

FIGURES

Page

I - 1 Projected Electric Generation by Types of Prime Mover. . . . . I - 5

I - 2 Simplified Schematic Heat Balance Diagram for a Super Critical Double Reheat Cycle . . . . I - 15

I - 3 Temperature-Entropy Diagram I - 17

II - 1 Growth Rate of E. Coli . . . . II - 8

III - 1 Simplified Aquatic Food Web. . . . . III - 4

III - 2 Typical Histograms of Various Degrees of Pollution . III - 5

III - 3 Diversity-Density Distribution for Unpolluted (Upper Curve) and Polluted (Lower Curve) Streams . . III - 7

III - 4 Algae Population Shifts with Change in Temperature . III - 8

III - 5 Median Resistance Times for Fish Acclimated to 20°C . . . . III - 11

III - 6 Effect of Acclimatization Temperature on Upper Lethal Limit of Speckled Trout . . . . III - 12

III - 7 Upper and Lower Lethal Temperatures for Young Sockeye Salmon . . . . III - 14

III - 8 Relationship Between Temperature and Active and Standard Levels of Oxygen Uptake . . . . III - 16

III - 9 Difference Between Maximum and Standard Levels of Oxygen Uptake (Lower Curve) and Speed at which Goldfish Can Swim Steadily at Various Temperatures . . . III - 16

III - 10 Relation of Oxygen Uptake to Temperature in Acclimated Speckled Trout . . . . III - 17

III - 11 Interrelationships of Biochemical Changes During Cold Acclimation . . . . III - 30

FIGURES (cont.)

Pages

III - 12 Comparison of ORSANCO Water Standards with Ohio River Water and Recommended Temperatures . . . . . III - 60

IV - 1 Typical Stratified Reservoir Profile . . . . IV - 3

IV - 2 Different Forms of Density Currents. . . . . IV - 4

IV - 3 Reservoir with Density Underflow . . . . IV - 6

IV - 4 Tagged Interflow Through Fontana Reservoir . . . . . IV - 8

IV - 5 Selective Withdrawal as an Interflow . . . . IV - 9

IV - 6 Distribution of Water Quality Parameters Under Isothermal Conditions . . . . IV - 12

IV - 7 Redistribution of Water Quality Parameters Under Stratified Conditions. . . . . IV - 13

IV - 8 Self-Purification as a Function of Temperature . . . IV - 16

IV - 9 Oxygen-Sag Curve-Free Flowing Condition. . . . . . . IV - 17

IV - 10 Oxygen-Sag Curve-River Impounded . . . . IV - 19

IV - 11 Permissible Waste Load at 4 ppm D. O. . . . . IV - 20

VI - 1 Run of the River Electricity Generating Station Cooling System . . . . VI - 2

VI - 2 Mechanisms of Heat Transfer Across a Water Surface . VI - 4

VI - 3 Heat Dissipation From Water Surface by Evaporation, Radiation, Conduction, and Advection During January and June . . . . VI - 5

VII - 1 Schematic Diagram for Stratified Flow . . . . VII - 6

VII - 2 Critical Sections in Stratified Flow . . . . VII - 12

VII - 3 Dead Zones in Streams . . . . VII - 55

VII - 4 Comparison of Dispersed Flow Model with Dead Zone Model . . . . VII - 59

FIGURES (cont.) Page

VIII - 1 Congruency Diagram for Overflow Condition. . . . . VIII - 10
X - 1 Schematic of Cooling Towers. . . . . X - 3
X - 2 Heller Type Dry Cooling Tower System . . . . X - 18

TABLES

Page
I - 1 Nuclear Power Costs. I - 7
I - 2 Net Heat Rates for Steam-Electric Generating Stations 1925 to 1964. . . . . I - 10
I - 3 Average Condenser Water Requirement and Consumptive Use for Fossil-Fueled Steam Electric Power Plants 1965 to 2020 . . . . I - 13
I - 4 Projected Fresh Water Requirements for Steam Electric Power Generation 1965 to 2020 . . . . I - 13
I - 5 Approximate Correction Factors for Condensing Steam Plants . . . . I - 16
II - 1 Water Properties as a Function of Temperature. . . . . II - 2
II - 2 Variation of θ with Temperature. . . . . II - 6
III - 1 Taxonomic Grouping of Organisms and Interpretation of Results . . . . .III - 6
III - 2 Known Instances of Thermal Caused Fish Kills . . . . .III - 22
III - 3 Effect of Condenser Passage Upon Dissolved Oxygen of Cooling Water (Markowski) . . . . .III - 38
III - 4 Effect of Condenser Passage Upon Dissolved Oxygen of Cooling Water (Trembley). . . . . .III - 40
III - 5 Recommended Maximum Temperatures of Fish by the National Technical Advisory Committee on Water Quality Criteria . . . . .III - 54
III - 6 Limiting Temperature Criteria in Water Quality Standards for Interstate Waters. . . . . .III - 57
VI - 1 Comparison of Stream Temperature Prediction Models . . VI - 37
VII - 1 Laboratory Data on Momentum Jets . . . . .VII - 29

TABLES (cont.) Page

VII - 2 Experimental Data for Three-Dimensional Jets . . . . VII - 33

XI - 1 Climatic Changes Produced by Cities. . . . . XI - 4

XII - 1 Economic Comparison of Cooling Methods . . . . XII - 5

XII - 2 Economic Comparison of Cooling Towers. . . . . XII - 7

XII - 3 Equivalent Fuel Costs. . . . . XII - 6

XII - 4 Unit and Total Costs of Cooling Devices. . . . . . . XII - 11

CHAPTER I-1

INTRODUCTION

The problem of thermal pollution has impinged upon our consciousness because of the tremendous growth in the use of electric energy, in the size of the central electricity generating stations, and the transition from fossil fuels to nuclear fuels.

The first questions we must ask are how serious is the thermal pollution problem? What is the potential magnitude of the problem? We, first, can note that any large scale modification of the thermal regime of rivers and reservoirs will change its ecology and usually for the worse. The most obvious and destructive change is the heat killing of fish. Less obvious but possibly equally destructive in the long run may be the sublethal effects. Though only a small number of fish kills due to thermal changes have occurred to date, if unrestricted use of streams and reservoirs for cooling purposes were allowed, the number would greatly increase. Therefore, the concern is primarily to prevent a potential major pollution problem from occurring. In addition, discharges of heated waters are equivalent to the discharges of organic wastes in lowering the assimulative capacity of a stream. The cooling water requirements for even a 20°F rise is greater than the minimum daily flow of the Mississippi River at Vicksburg (Mathur, 1968).

The greatest single source of man made heat addition to our waterways is from electric generating plants. Analysis of steam electric cooling discharges indicate an average 15°F rise in water temperatures after passing through condensers (Water Resources Council, 1968). The amount of water withdrawn for this purpose is approximately 40 trillion gallons per year which is roughly 10% of the total flow of waters in U.S. rivers and streams per year (Water Resources Council, 1968). Industrial cooling water discharges are approximately 10 trillion gallons per year (Water Resources Council, 1968). The magnitude of the industrial cooling water volume, however, is fraught with a great deal of uncertainty because of the great difficulty in evaluating and obtaining definitive information on industrial cooling water uses. The plants differ widely among themselves, even within the same industry. The temperature of the discharge waters are less critical and consequently the information is not as satisfactory as that available from the steam electric generating plants. We can, however, conclude that this source will not be as concentrated nor as troublesome, as discharges from electric generating plants. Their relative impact can be assessed by the Federal Water Pollution Control Administration estimated costs of total cash outlays from 1969 through 1973 for cooling steam generating stations discharges approximately 2 billion dollars and for cooling manufacturing discharges 700 million (Department of the Interior, 1968).

In addition to the power plant and industrial waste heat additions to waterways, modest increases in the heat load of the waters are caused by municipal and irrigation return waters. Published information on the temperature rise of water from intake plants through the discharge point of the sewage treatment plant is sparse. On the Thames Estuary it was reported that sewage effluents are responsible for 9% of the heat additions to the stream (Gameson, Hall, Preddy, 1957). The remainder of the heat additions to the stream are detailed below:

Source of Heat	Percentage of Total
Power Stations	74.5
Industrial Effluents	6
Sewage Effluents	9
Fresh Water Discharges	6.5
Biochemical Activity	4

For Nashville, Tennessee, for a typical year the average temperature rise through the system is 3.5°F. (Personal communication, G. A. Johnson, 1969). Analysis of other cities' data is underway.

Return flows from irrigation fields are also a thermal pollutant. As in any environmental situation the actual rise is a function of many things, including the initial water temperature, volume of abstraction, velocity of flow, length of time in field, and climatic conditions. For one site in the State of Washington, the rise has been found to be from 9° to 19°F (Eldridge, 1963).

A. CENTRAL ELECTRICITY GENERATING STATIONS

i. Growth in central station energy requirements

The really significant heat loads result from the discharge of condenser cooling water from the ever-increasing number of steam electrical generating plants. Electrical power generation in the United States has doubled every ten years since 1945 and all indications are that the rate of increase will be even greater during the next few decades. Furthermore, the problems associated with these concentrated heat loads are compounded by the increased size of individual power plants and the greater quantities of heat discharged by equivalent size plants when nuclear power reactors are used.

It has been estimated that the 95% of the centrally generated electricity that is produced by fossil fuel today will be 65% nuclear by the year 1980 (Bregman, 1968). As will be shown subsequently, large nuclear power plants currently require approximately 50% more cooling water for a given temperature rise than do fossil fuel plants of equal size. It is expected that improved technology will reduce this added requirement to 25% by the year 1980. Development of nuclear breeder reactors will reduce the amount of heat to be dissipated to that of fossil-fueled plants; however, these are not expected to be available until the 1980's (Seaborg, 1968).

The Atomic Energy Commission (1968) stated that as of June, 1968, 13 nuclear central-station electric power reactors were in operation, 21 were being built and 40 were being planned. The increase in size of the newer power stations is indicated by noting that the nuclear power plants planned for operation by 1973 average 624 megawatts per unit while those retired between 1962 and 1965 averaged 22 megawatts per unit (Bregman, 1968).

Figure I-1 shows the anticipated growth of the power industry until the year 2020. One should note the relatively small percentage of power production that is and will be contributed by sources other than steam generation.

In 1964, hydro-electric plants provided 19% of the capacity and energy produced and indications are such that this will continue to decline as shown on Figure I-1 (Water Resources Council, 1968). Though economical sites for electric power development are being eliminated, potential sites for pumped storage installations still exist in the United States (Federal Power Commission, 1968). The optimal use of pumped storage is for peaking power and reserve capacity since the large steam electric plants being constructed operate best at high plant factors which are complemented by the low plant factors of the pumped storage plants.

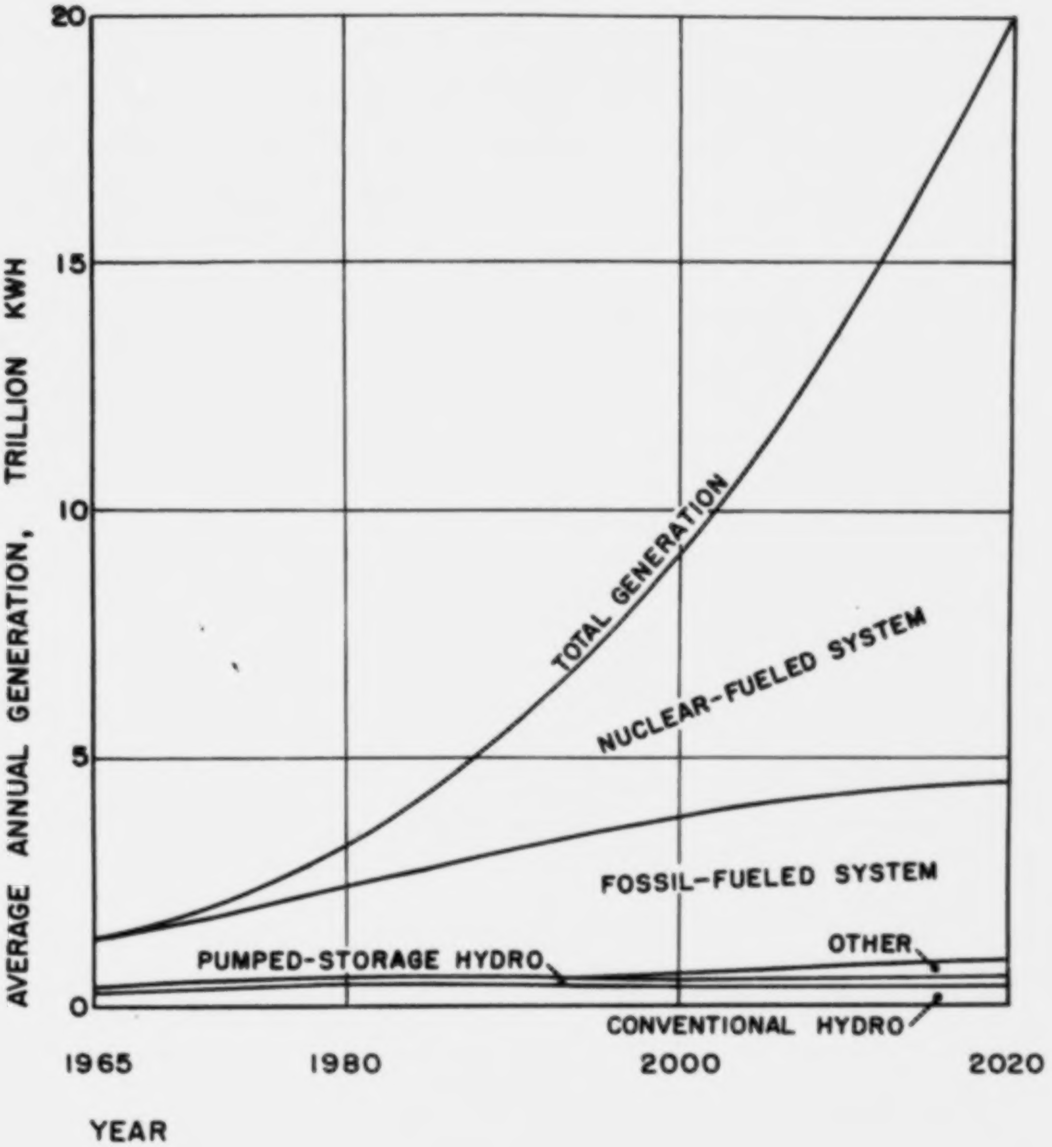


FIGURE I - 1 PROJECTED ELECTRIC GENERATION BY TYPES OF PRIME MOVER

The rate of growth in electric usage is not only due to the increase in population but also because the use of electricity per family unit is also increasing as we go to electric space heating, wider use of air conditioning and a plethora of electric appliances of dubious utility. Another factor which intensifies the thermal pollution problem is that over 50% of the generating capacity ordered recently has been nuclear, primarily light water reactors. The thermal efficiencies of the light water reactors contracted for recently have been on the order of 34% in comparison to the 40% for equivalent fossil fueled plants. As long as light water reactors predominate, and this seems to be likely for a number of years, we can expect that the thermal efficiencies of the nuclear power plants will be below that of equivalent fossil fuel electric generating plants. The reason for this is the lower temperatures and pressures in reactor shells. This will continue because the AEC has dropped many of the projects for advanced converters and for super heat and reheat of the light water fuel reactors because of metallurgical problems and seems to be going for fast breeder reactors as its next major step.

However, the preponderance of nuclear commitments may be on the wane as the rise in costs of nuclear power plants has been considerably above that for fossil fueled plants since the low of the Browns Ferry first and second units as shown in Table I-1 (Sporn, 1967). At that time nuclear power plants were competitive with fossil fuels at 16 cents per thousand BTU's. A recent large nuclear power plant, the Surry, is competitive with fossil fuel at 24.83 cents per thousand BTU's, which shows the rate at which nuclear power costs have increased relative to fossil fueled plants.

TABLE I - 1

NUCLEAR POWER COSTS *

Year	Atomic Unit	Size (megawatts)	Cost of Station (per kilowatt)	Total Production Cost (mills per kilowatt-hour)	Competitive Point (cents per million B.T.U.)
1964	Post-Oyster Creek	605.0	$139	4.48	26.3
1965	Post-Dresden 2	800.0	$123	4.42	24.0
1966	Browns Ferry 1, 2	1,100.0	$115	3.78	16.0
1967	Browns Ferry 3	1,100.0	$132	4.04	19.0
1967	Bridgman	1,100.0	$139.50	4.30	21.95
1967	Surry	815.5	$152.55	4.55	24.83

* After Sporn

ii. Growth in size

We can also expect that the thermal problems associated with cooling water discharges from steam electric generating plants will even further exceed the problems from industrial sources because it appears that industrial plants have by and large already reached the maximum economically efficient size and decentralization seems to be more important now whereas in steam electric generating plants, we may note that in the last fifteen years the maximum size of the generating units has risen from 208 Mw to 1100 Mw. In addition, the increase in size of individual units has made a great difference in the intensity of the thermal pollution problem. Although the total amount of heat disposed of to the environment may not increase when a single 1100 Mw plant is built rather than two 550 Mw plants at separated sites, the impact is far greater because the amount of dilution immediately available is greatly decreased and the heat losses to the atmosphere between sites does not occur. The units being installed at Brown's Ferry will be 1100 megawatts and consequently, even if the unit rate of release of heat were the same, the increase in size of units means that a greater amount of heat is being discharged at a point to the same size stream.

iii. Efficiency - Heat Rate

It is also true, of course, that the efficiency of these units has increased over the years. The average net heat rate dropped from 25,000 BTU per kilowatt hour in 1925 to 10,453 BTU per kilowatt hour in 1965, so we have seen a net heat rate decrease at a 2.8% annual rate over the last 40 years whereas total power generation has increased at a 7.2% annual rate and the unit sizes have increased at an 18% annual rate over the last 15 years. At present we seem to be approaching the upper limits of efficiency in fossil fuel steam generation at a heat rate of about 8500 BTU's/kwhr, which is an overall efficiency of about 40%.

Current generally accepted maximum operating conditions for conventional thermal stations are 1000°F and 3500 psi, with a corresponding heat rate of 8700 BTU per kwh, 3413 BTU's resulting in power production and 5287 BTU's being wasted. Plants have been designed for 1250°F and 5000 psi; however, metallurgical problems have held operating conditions to lower levels.

Nuclear plants operate at temperatures from 500 to 600°F and pressures up to 1000 psi, resulting in a heat rate of approximately 10,500 BTU/kwh. Thus, for nuclear plants, 3413 BTU's are used for useful power production and 7087 BTU's are wasted.

Table I-2 details the increasing efficiencies that have resulted from significant improvements in the conventional steam cycle (Federal Power Commission, 1964). Future heat rate gains will be minimal, however, because supercritical pressures of 3500 to 5000 psi and temperatures of 1100 to 1200°F are reflected in the data for 1961 and 1962. Present day central station average thermal efficiency is said to be 33% and the present best performance, 42%.

This is the most economic efficient rate. It is possible to arrive at a higher efficiency than this but the total costs are greater and therefore this is most likely the best plant heat rate that can be expected in the near future. It we compare this 40% efficiency with the Carnot cycle, using again the most economic temperature of 1050°F and the average temperature of surface waters in coterminous U.S. of 55°F, one then arrives at a Carnot cycle efficiency of 66%. Therefore, our 40% efficiency for the most economically efficient plant is actually 61% of the maximum possible efficiency.

TABLE I-2

NET HEAT RATES FOR STEAM-ELECTRIC GENERATING STATIONS 1925 TO 1964

Year	Best Plant[2] BTU/KWH	Best System BTU/KWH	U.S.[1] Average BTU/KWH
1925	15,000	[3]NA	25,000
1930	12,900	NA	19,800
1935	12,300	NA	17,850
1936	10,954	NA	17,800
1937	10,779	NA	17,850
1938	10,788	NA	17,450
1939	10,770	NA	16,700
1940	10,729	NA	16,400
1941	10,606	NA	16,550
1942	10,596	NA	16,100
1943	11,021	NA	16,000
1944	10,689	NA	15,850
1945	10,345	NA	15,800
1946	10,608	12,715	15,700
1947	10,600	NA	15,600
1948	10,588	NA	15,738
1949	10,437	NA	15,033
1950	9,378	11,876	14,030
1951	9,379	11,676	13,641
1952	9,303	11,665	13,361
1953	9,329	11,185	12,889
1954	9,113	10,660	12,180
1955	9,151	10,270	11,699
1956	9,106	9,780	11,456
1957	9,118	9,705	11,365
1958	9,130	9,760	11,085
1959	9,011	9,620	10,970
1960	8,975	9,590	10,760
1961	8,760	9,363	10,650
1962	8,588	9,390	10,558
1963			10,482
1964			10,462

[1] Exclusive of Alaska and Hawaii.

[2] Plants in service full year.

[3] NA - Not Available.

It cannot be expected that in this cycle the efficiencies can be driven much higher.

One should perhaps not compare the steam cycle with the Carnot cycle, since the Rankine cycle more nearly approximates the actual cycle in a steam plant. However, the Carnot cycle is the reversible cycle possessing the hgihest possible thermal efficiency. In the Carnot cycle heat is supplied at the highest temperature, rejected at the lowest temperature, and undergoes adiabatic expansion and compression. The efficiency of the Carnot cycle may be computed by the differences in the absolute temperature of the heat added and rejected, divided by the absolute temperature of the heat added. Therefore, as indicated above, with the heat added at a temperature of (1050° + 460°) 1510°R and rejected at 55° + 460°) 515°R, the thermal efficiency is 66%.

The Rankine cycle is more nearly representative of a modern steam plant because it does not include an adiabatic compression step. Instead, heat is added to the feed water, bringing it to a boil and converting it to steam. The distinguishing contrast is between the isentropic compression of the Carnot cycle and the heat added to the pressurized water until the critical point.

The best efficiencies for present day light water reactors is about 34%, which means that the overall amount of heat discharged to receiving waters from nuclear fuel power generating stations is greater than from fossil fuel power generating stations, but the problem itself is not substantially changed. We can, however, look forward to improved efficiencies in the high temperature gas reactors and in the breeder reactors when they do come on line. Rosenthal, et al, (1965) estimates that the high temperature gas cooled reactor of 1000 Mw will have a thermodynamic efficiency of 44.4%.

Kasten (1966) estimates that the net thermal efficiency of a 1000 Mw molten salt breeder reactor will be 44.9%.

From this fairly extensive discussion of the future growth of the thermal pollution problem and the sources of heat, we can see that there is not much hope with the present technology and forseeable technology to decrease to any substantial degree the total amount of heat rejected to streams from these central steam generation plants. The interdepartmental energy study under the direction of Ali Cambel (1966) stated, "Further cost reductions in conventional central power stations will be difficult to attain in view of the high internal efficiencies and the economies of plant size already realized."

B. COOLING WATER REQUIREMENTS

It has been estimated that cooling water requirements will increase from 50 trillion gallons per year in 1968 to 100 trillion gallons per year by 1980, and that this will be approximately one-fifth of the total runoff in the coterminous United States. Actually, the major portion of water may be used for other beneficial purposes or reuse. Examination of Table I-3, which is the Water Resources Council's estimate of cooling water requirements and consumptive use based on a temperature rise of 15°F, demonstrates the consumptive use per kwhr in fossil-fueled steam electric power plants (Water Resources Council, 1968). The predicted decrease in unit water requirements is based on improved technology.

Table I-4 (Water Resources Council, 1968) gives the total daily fresh water requirements for cooling and consumptive use for steam electric power generation for the years 1965 to 2020.

TABLE I-3

AVERAGE CONDENSER WATER REQUIREMENT AND CONSUMPTIVE USE FOR FOSSIL-FUELED, STEAM-ELECTRIC POWER PLANTS, 1965 - 2020

(Gallons per KWH)

Year	Condenser Requirements	Consumptive Use		
		Once Through	Cooling Ponds	Cooling Towers
1965	 40	0.3	0.4	0.5
1980	 35	0.2	0.3	0.4
2000	 30	0.15	0.25	0.35
2020	 25	0.1	0.2	0.3

TABLE I-4

PROJECTED FRESH WATER REQUIREMENTS FOR STEAM ELECTRIC POWER GENERATION - 1965 - 2020

	Million Gallons/Day			
	1965	1980	2000	2020
Condenser Requirement	84,800	216,400	477,700	806,400
Withdrawn	68,500	141,500	267,200	419,600
Consumptive Use	758	1,760	4,645	8,110

C. IMPROVING EFFICIENCY OF CENTRAL STATION STEAM ELECTRICITY GENERATION

To increase the efficiencies of central steam electricity generating stations, it is possible to increase boiler pressure, decrease the back pressure, increase the temperature of the inlet steam, increase the temperature of the feed water by using a portion of the steam taken from turbine prior to the condenser, and reheat steam taken from the turbine and reinjected into the turbine after being reheated in the boiler. The approximate increases in efficiency for each of these changes is shown in Table I-5 (Babcock and Wilcox, 1963). A schematic of a steam plant incorporating all of the efficiency increasing items is shown below in Figure I-2.

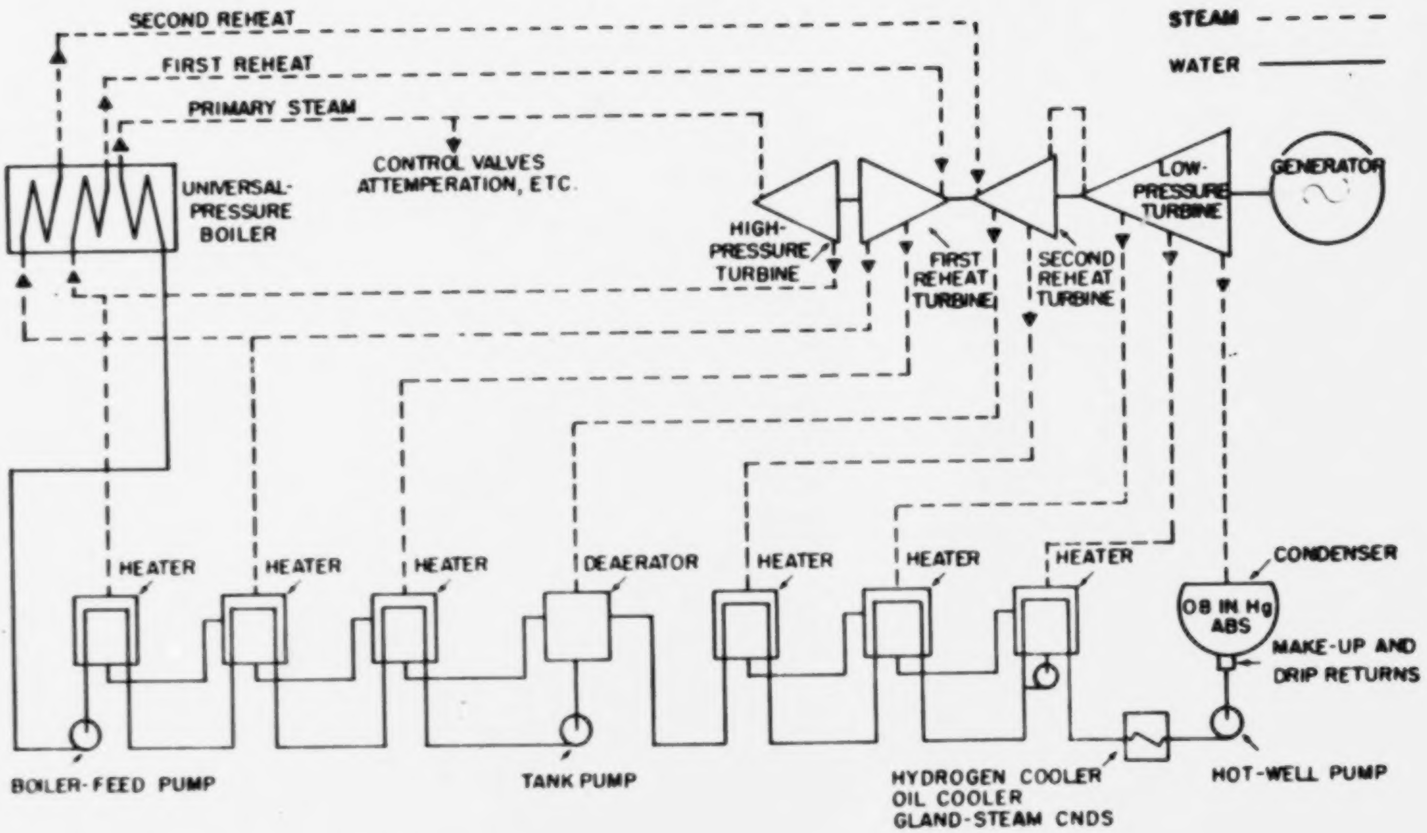

SECOND REHEAT
FIRST REHEAT
PRIMARY STEAM
CONTROL VALVES
ATTEMPERATION, ETC.
UNIVERSAL-PRESSURE BOILER
HIGH-PRESSURE TURBINE
FIRST REHEAT TURBINE
SECOND REHEAT TURBINE
LOW-PRESSURE TURBINE
GENERATOR
STEAM
WATER
HEATER
HEATER
HEATER
DEAERATOR
HEATER
HEATER
HEATER
CONDENSER
0.8 IN Hg ABS
MAKE-UP AND DRIP RETURNS
BOILER-FEED PUMP
TANK PUMP
HYDROGEN COOLER
OIL COOLER
GLAND-STEAM CNDS
HOT-WELL PUMP

FIGURE I - 2 SIMPLIFIED SCHEMATIC HEAT BALANCE DIAGRAM FOR A SUPER CRITICAL DOUBLE REHEAT CYCLE

TABLE I - 5

APPROXIMATE CORRECTION FACTORS
FOR CONDENSING STEAM PLANTS

Initial Conditions:					
Pressure, psi	400	600	850	1250	2000
Temperature, F	800	825	900	950	1050
Reheat Temp., F	-	-	-	-	1000
Corrections for:					
Pressure, Btu/psi	3.3	2.3	0.7	0.55	0.3
Initial temp, Btu/F	4.3	3.8	3.0	3.0	1.3
Reheat temp, Btu/F	-	-	-	-	1.2
Vacuum, Btu/in. Hg	320	220	200	200	200
Feed temp, Btu/F	1.5*	1.4*	1.1*	0.8*	1.5†

*Change in boiler efficiency is not included.
†Change in boiler efficiency is included.

Note: Corrections represent the change in net plant heat rate (Btu per net kwhr) per unit change in variable.

The idealized temperature - entropy diagram is shown below in Fig. I-3.

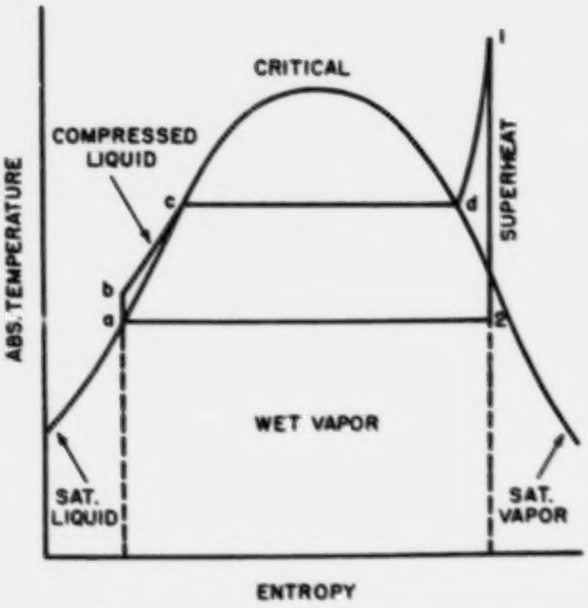

CRITICAL
COMPRESSED LIQUID
ABS. TEMPERATURE
SUPERHEAT
1
c
d
b
a
2
WET VAPOR
SAT. LIQUID
SAT. VAPOR
ENTROPY

FIGURE I - 3 TEMPERATURE-ENTROPY DIAGRAM

Where:

a - b Boilerfeed water is pressurized in pump.

b - c Heat is added to the feed water through regenerative feed water heaters.

c - d Heat is added in the boiler, turning water to steam.

d - 1 Heat added in boiler raising steam temperature to superheated steam.

1 - 2 Steam expands in high pressure turbine until steam starts to condense.

2 - a Steam condensed in condenser.

The area inside the heavy lines (a-b-c-d-1-2-a) is the work done, whereas the area under a-b-c-d-1-2 is the heat added. It can readily be seen that if the area under a-2 (heat rejected) is held constant then any increase in the area above will increase the thermodynamic efficiency though not necessarily the economic efficiency.

D. ALTERNATIVE METHODS OF CENTRAL STATION ENERGY PRODUCTION

It has been noted that increased thermal efficiencies from fossil fueled steam plants have reached a plateau from which they are not likely to rise dramatically. In addition, it has also been noted that high temperature gas and molten salt breeder nuclear reactors will increase their efficiency only slightly. Therefore, it might be instructive to investigate other possible central station power sources.

Fuel cells which produce electricity through redox reactions in an electrolyte and are not subject to Carnot cycle efficiencies are already proving extremely useful in space applications in the 1 - 2 Kw (Hydrogen - Oxygen) size (Barak, 1968). General Motors has demonstrated a 32 Kw hydrogen - oxygen battery for motor cars (Barak, 1968). In Sweden a 200 Kw battery is being built for use in a submarine. To date there has been no use for large scale stationary power sources. However, Archer (1968) has suggested somewhat optimistically that the design of a 100 Mw commercial fuel cell power plant will be available by 1974. Though the costs for space and moving source applications are excessive for large scale stationary power sources, United Engineers and Constructors for a large scale stationary power source estimates a capital cost of $90/kilowatt and a power cost 2.9 mills per kilowatt hour (Archer, 1968). The main advantages of a fuel cell system would be high efficiency (depending upon fuel and fuel preparation) from 60 - 68%, no cooling water requirement, and minimized air pollution. Westinghouse expects to build such plants within a decade (Archer, 1968). One interesting concept utilizing fuel cells is the TARGET program, where natural gas would be used to supply the energy for space and water heating and cooling and when natural gas would be used in a fuel cell to generate the electricity required (Barak, 1968).

Magnetohydrodynamic power generation in which a gaseous conductor has moved through a magnetic field to generate electricity has been generally considered as the most likely new system for use in the central power station. Though many engineering problems remain to be solved, the Soviet Union is building a 75 Mw pilot plant in Moscow and a 20 Mw unit is installed at the Tullahoma Arnold Engineering Development Center for hypersonic wind tunnel use. MHD systems with single cycles can achieve thermal efficiencies of 50-55%, which could possibly be boosted to 60-70% by using a binary cycle (Rosa and Hals, 1968). If a binary cycle using a gas turbine is utilized, the thermal pollution problem is avoided entirely. However, even the most ardent advocates of MHD agree central station use is at least 10 years away, and the International MHD Liason group concluded in 1967 that the economics of the open cycle were not yet fully established and that insufficient information was available on the performance of closed cycle systems. Recent studies indicate that with the decrease in fossil fuel and nuclear power costs it may be quite difficult for the MHD topping cycle to be economically competitive (Evans, 1968). It might be of interest to note that Britain's Central Electricity Generating Board has abandoned its MHD research efforts. Too much should not be read into this though because Britain is also cutting back drastically on its fusion research. Both these cuts may be due to economic difficulties rather than technical feasability or promise.

Electrogasdynamics is a system of producing power by the conversion of the energy of flowing gases into electricity without moving mechanical parts. Though heralded as a money saving, high efficiency and low water requirement system, (Gourdine and Malcolm, 1966) and still touted by its advocates, the Office of Coal Research has recently terminated its contract.

The only other serious contender at the present time is fusion power. Fusion is extremely attractive, as it would provide a virtually unlimited source of energy. However, before a satisfactory system is ready, a great deal of work in plasma physics and engineering is required. In particular, a high density plasma must be confined and heated to thermonuclear temperature. The engineering development of the vacuum wall, blanket, and chemical processing plant must then be carried out. Even the most optimistic fusion partisans believe that it will not be until the 1980's before fusion power is at the state of fission power today. In addition, fusion power will still be limited by Rankine cycle efficiencies though they may be higher than present day steam plants through the use of topping cycles.

Direct use of power from the sun has also been investigated (Glaser, 1969), but the near term use in central station power plants is not promising. The role of thermal electricity and thermionics in central station research seems to be limited.

Therefore, we may conclude that the amount of waste heat to be released will continue to grow and the hopes of any great reduction by increased efficiency will be negated by the overall rise in the utilization of electrical power.

The possibilities of dilution must be considered next. The average flow of water in U. S. rivers and streams is about 440 trillion gallons per year. It does not seem likely that there is any great possibility of substantially increasing this amount. The NAS-NRC Report "Weather and Climate Modification - Problems and Prospects" has indicated that artificial seeding has produced some evidence for precipitation increases of as much as 10 or even 20 percent over areas as large as 1000 square miles over periods ranging from weeks to years (National Science Foundation, 1966).

A twenty percent increase in the flow of all rivers while welcome and useful would not, however, solve the problem. It would also be possible through the use of low flow augmentation techniques, etc., to even out the flow during the course of the year, but this still would not solve the problem. Therefore, since technological help in the form of increased efficiencies in energy utilization or by major additions to dilution water are remote, one must turn to means of dissipating the heat directly to the atmosphere and to restricted water bodies, rather than to streams and reservoirs.

E. ALTERNATIVE METHODS OF HEAT DISSIPATION

It has already been shown that there exists little likelihood of such increases in thermal efficiencies in conventional power sources or of practical application of new power sources that the major portion of heat generated will be effectively used. It has also been shown that the possibilities of increased diluent water flow through weather modifications or low flow augmentation are such that disposal to the atmosphere will be the major methodology to be utilized in the future.

In the water short regions of the country, this is already the case. In the Colorado region the use of cooling towers and ponds is already well established. Nineteen out of twenty-two plants having a capacity of 100 megawatts or greater are already using these auxiliary cooling devices. Already, in 1965, over 22.5% of the plants greater than 100 megawatts in the nation used cooling ponds or towers (Department of the Interior, 1968).

F. RESEARCH REQUIRED FOR ALTERNATE MEANS OF ELECTRICITY GENERATION

Due to the necessity of reducing the amount of heat discharged to our waterways, systems capable of achieving higher efficiencies must be developed.

1. Topping Cycles - It may be worthwhile to reexamine the use of topping cycles and see if the economics have sufficiently changed to justify further development.

2. Magnetohydrodynamics - Of all the new energy systems MHD appears to be closest to achieving an economically competitive system. Research should be pushed on its development.

3. Breeder Reactors - Because liquid metal cooled reactors can operate at higher temperatures than water cooled reactors, high efficiencies could be obtained. Work should be accelerated on these higher thermal efficiency systems.

4. Gas Cooled Reactors - High temperature gas cooled reactors can operate at higher thermal efficiencies than water reactors. Their application should be studied further.

5. Fusion Reactors - The possibility of direct conversion to electricity, offers such a large reduction in waste heat and lower power costs that studies should be continued.

BIBLIOGRAPHY

Archer, D. H., 1968, "Fuel Cells For Central Power Generation", Mechanical Engineering.

Babcock and Wilcox Company, 1963, Steam, Babcock and Wilcox Co., New York, N. Y.

Barak, M., 1968, "Fuel Cells - Problems for Chemical Engineers", Chemical and Process Engineering

Bregman, J. I., 1968, "Thermal Pollution Control - Need for Action", paper presented at Thermal Pollution Symposium of the Cooling Tower Institute, New Orleans, La.

Cambel, A. B., 1964, "Energy R & D and National Progress", U. S. Government Printing Office, Washington, D. C., XXXI.

Department of the Interior, Federal Water Pollution Control Administration, 1968, The Cost of Clean Water, II

Eldridge, E. F., 1963, "Irrigation as a Source of Water Pollution", Journal of Water Pollution Control Federation.

Evans, R. K., 1968, "MHD Topping Cycles, A Reassessment", Power

Federal Power Commission, 1968, "Hydroelectric Power Evaluation," U. S. Government Printing Office, Washington, D. C.

Federal Power Commission, 1964, "National Power Survey, Part 1", U. S. Government Printing Office, Washington, D. C.

Gameson, A. L. H., Hall, H., and Preddy, W. S., 1957, "Effects of Heated Discharges on the Temperature of the Thames Estuary", Engineer, 204, 850.

Glaser, P. E., 1969, "Power From the Sun", Mechanical Engineering, 24.

Gourdine, M. C., and Malcolm, D. H., 1966, "Energetics 2: Electrogasdynamic ", Mechanical Engineering, 48.

Johnson, G. A., 1969, Personal Communication.

Kasten, P. R., Bettis, E. S., Robertson, R. C., 1966, "Design Studies of Reactors," 1000 MW(e) Molten Salt Breeder ORNL-3896, Oak Ridge National Laboratories, Oak Ridge, Tenn.

Mathur, S. P., 1968, "Waste Heat from Steam-Electric Generating Plants Using Fossil Fuels and Its Control", FWPCA, Cincinnati, Ohio.

National Science Foundation, 1966, "Weather Modification", U. S. Government Printing Office, Washington, D. C.

Rosa, R. J., and Hals, F. A., 1968, "In Defense of MHD", Industrial Research.

Rosenthal, M., 1965, "A Comparative Evaluation of Advanced Converters", ORNL 3686, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Seaborg, G. T., 1969, "Looking Ahead in Nuclear Power", Mechanical Engineering.

Sporn, P., 1968, "Nuclear Power Economics, 1962 - 1967,", U. S. Government Printing Office, Washington, D. C.

U. S. Atomic Energy Commission, "Nuclear Reactors Built, Being Built, or Planned in the United States as of June 30, 1968", TID 8200 (18th Rev), U. S. Government Printing Office, Washington, D. C.

Water Resources Council, 1968, "The Nation's Water Resources", U. S. Government Printing Office, Washington, D. C.

CHAPTER II - 1

PHYSICAL, BIOLOGICAL, AND CHEMICAL EFFECTS ON WATER QUALITY

A. Physical

Temperature affects nearly every physical property of concern in water quality management including density, viscosity, vapor pressure, surface tension, gas solubility and gas diffusion. Table II-1 details the change in these properties with change in temperature.

The solubility of oxygen is probably the most important of these parameters, inasmuch as dissolved oxygen in water is necessary to sustain many forms of aquatic life. Obviously, the lower solubility induced by higher temperatures, if combined with an organic load and an increased bacterial respiration rate, could lead to such low levels of oxygen that fish could not survive.

Since vapor pressure is a driving force in evaporation, an increase in temperature will cause an increase in evaporation, assuming other factors to be constant. Evaporation is one of the key mechanisms in cooling water bodies.

TABLE II - 1

WATER PROPERTIES AS A FUNCTION OF TEMPERATURE

Temperature °C	Vapor Pressure mm.Hg	Viscosity Centipoise	Density gm/ml	Surface Tension Dynes/cm.	Oxygen Solubility mg/l	Oxygen Diffusivity cm^2/sec
0	4.579	1.787	0.99984	75.6	14.6	
5	6.543	1.519	0.99997	74.9	12.8	
10	9.209	1.307	0.99970	74.2	11.3	15.7
15	12.788	1.139	0.99910	73.5	10.2	18.3
20	17.535	1.002	0.99820	72.8	9.2	20.9
25	23.756	0.890	0.99704	72.0	8.4	23.7
30	31.824	0.798	0.99565	71.2	7.6	27.4
35	42.175	0.719	0.99406		7.1	
40	55.324	0.653	0.99224	69.6	6.6	

It also follows that increased temperature may lead to increased sedimentation in the receiving water, thus possibly adding to the sludge deposit problem. Because of the changes in the properties of water with temperature, changes in filtration, flocculation and ion exchange will also occur.

The increased temperature alone may also be a problem. McKee and Wolf (1963) report that water with a temperature of 10°C is usually satisfactory and waters with temperatures of 15°C or higher are usually objectionable for drinking purposes.

The effect of temperature on the reaeration coefficient, k_2, can be very important in determining the waste assimilative capacity of streams both below, above and in an impoundment. The reaeration coefficient increases monotonically with temperature as shown by Streeter and Phelps (1925).

$$k_{2(T^\circ C)} = k_{2(20^\circ C)} - 1.016^{(T^\circ C - 20^\circ C)} \qquad \text{II-1}$$

The precise mechanism by which temperature affects the reaeration rate constant is somewhat uncertain. O'Connor and Dobbins (1958) consider the effect to be through the change in the molecular diffusion coefficient of oxygen in water. Krenkel and Orlob (1963) proposed that the effect was caused by the greater proportion of oxygen molecules having the energy required to create a "site" in the water surface at higher temperatures. They noted that the requisite activation energy was about 5000 calories per mole, which is close to that for the flow of water. Because the water and oxygen molecules are approximately the same size, this result would be expected.

Both the O'Connor-Dobbins and Krenkel-Orlob theories predict a temperature effect which is essentially the same as that predicted by equation II-1. Dobbins (1964) maintained that the effect of temperature is variable, depending upon the turbulence of the water at the surface. The turbulence determines the relative importance of molecular diffusion or turbulent transport. The Dobbins model, which also considers the effect of temperature on surface tension and viscosity, predicts a change in k_2 of about 1.7% to 4.4% per degree in natural streams, depending on the turbulence intensity.

Support for this general pattern of behavior is provided by an analysis of the k_2 values measured by Thackston and Krenkel (1966) in a laboratory flume. Their equation, which was derived to describe the reaeration process at any scale of flow, may be put into the temperature-dependent form

$$k_2 = CW\theta^{(T-20)} \qquad \text{II-2}$$

in which:

$$W = \left[1 + \left(\frac{\bar{u}}{\sqrt{gh}}\right)^{1/2}\right]\sqrt{\frac{S_e g}{h}} \qquad \text{II-3}$$

C = constant

θ = temperature coefficient

S_e = slope of energy gradient

h = depth in feet

T = temperature in C

g = gravitational constant

Using experimentally measured values of k_2, W, and T, the best fit values of C and θ can easily be determined using the nonlinear least squares algorithm proposed by Marquardt (1963) and implemented by a digital computer program by Baumeister and Marquardt (1964). The use of the nonlinear least squares approach has been discussed previously by Thackston, et al. (1967).

For the entire body of laboratory data, the best value of θ was 1.0315, producing a change of 3.15% per degree of temperature change. The data were then divided into groups with different Froude numbers and the analysis was performed on each group. The results, which demonstrated that θ was a variable, are presented in Table II-2.

The theory of Dobbins predicts a range of θ for this turbulence and temperature range of about 1.05 to 1.02. The agreement is apparent, despite the fact that the temperature range of the measured data was relatively small, from 21.0° to 26.0° C.

The same analysis was performed on the data collected by O'Connor and Dobbins (1958) and Churchill, et al., (1962). The resulting values of θ were 1.0092 and 0.9797, respectively. In these cases, it is hypothesized that experimental error from other causes, common to field data was great enough to mask the variation in k_2 due to changing temperatures.

TABLE II-2

VARIATION OF θ WITH TEMPERATURE

Froude No. (1)	θ (2)	Percentage of Change Per Degree (3)
0.0 - 0.4	1.0589	5.89
0.4 - 0.6	1.0335	3.35
0.6 - 1.2	1.0253	2.53
Combined	1.0315	3.15

B. Biological

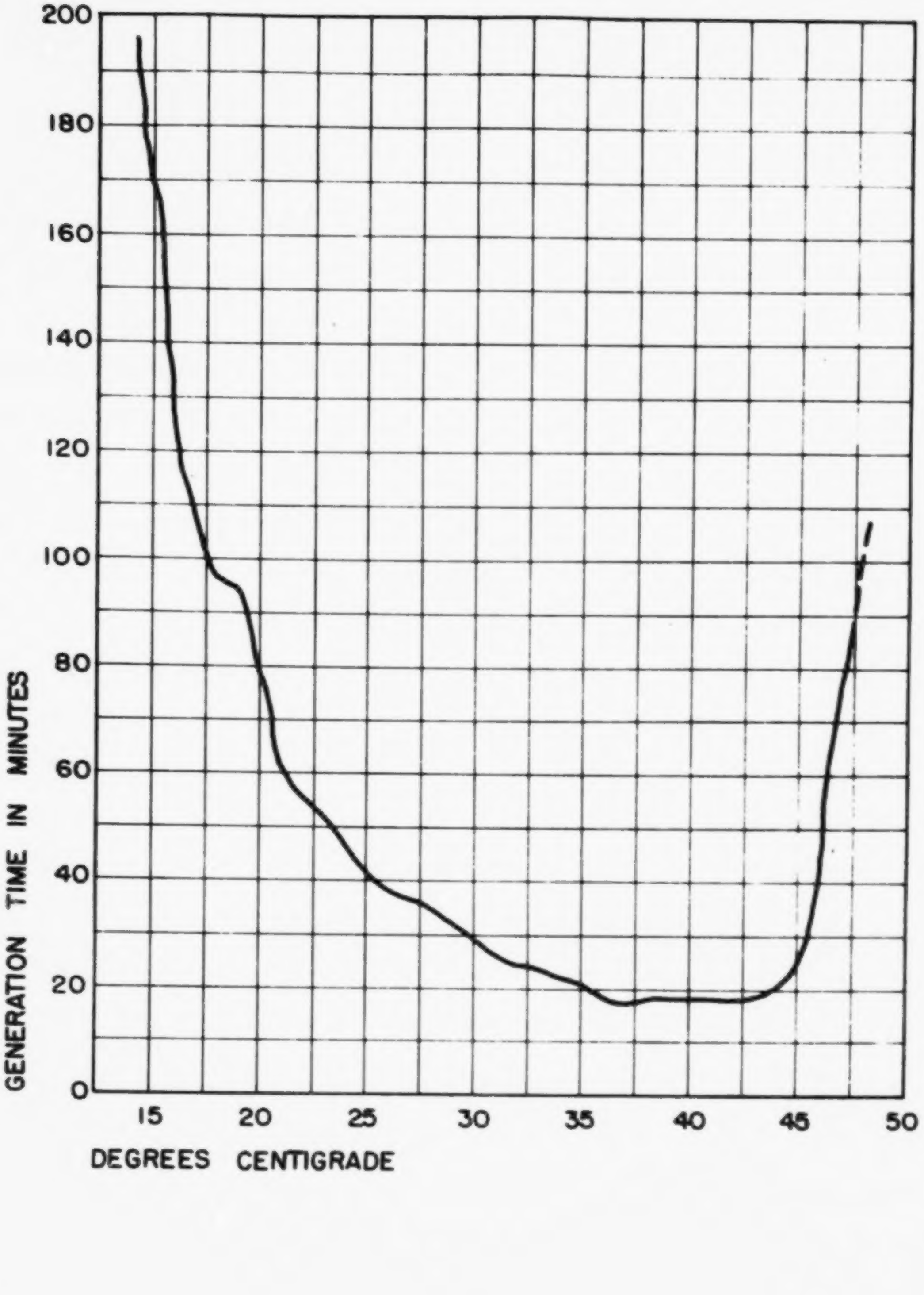
This section discusses temperature changes as they relate to purification processes only in the receiving water. According to Gunter (1957) temperature is the most important single factor governing the occurrence and behavior of life. Temperature effects on micro-organisms are significant to the biological processes of waste stabilization because of induced changes in growth rates and changes in death rates.

In general, the higher the temperature, the more active a microorganism becomes, unless the temperature or a secondary effect becomes a limiting factor. Thus, metabolic activity of thermophilic organisms is much greater at their optimum than psychrophilic organisms at their optimum. Examination of the known effects of temperature on waste treatment processes demonstrates the validity of this statement. It should be moted that a distinct difference exists between the ability of a microorganism to endure a given temperature and its ability to grow well under identical conditions.

The organism of particular interest to water quality management is E. Coli, as it is the prime indicator of fecal pollution. It is shown in Figure II-1 that increased temperatures may lead to optimum growth conditions for this organism in receiving waters.

The rate constant, k_1, which is conventionally used to describe the rate at which biological oxidation takes place in laboratory investigations is defined as:

$$\frac{dL}{dt} = -k_1 L \qquad \text{II-4}$$


GENERATION TIME IN MINUTES
200
180
160
140
120
100
80
60
40
20
0
15
20
25
30
35
40
45
50
DEGREES CENTIGRADE

where L = Biochemical Oxygen Demand, (B.O.D.),

t = time, days

k_1 = rate constant, days^{-1}

Temperature has a profound effect on the rate of oxidation. In the usual receiving water, a multitude of different organisms are active in waste assimilation, all with their own characteristics and temperature tolerances. The distribution of organisms may change drastically with shifts in temperature or types of waste, each species having a different rate of metabolism. Because the composite metabolism includes many coupled reactions, each with its own characteristics, the composite rate-limiting steps may shift with temperature changes, thus precluding the interpretation of the process as a single reaction. In addition, the increasingly rapid rates of protein denaturation, which takes place at temperatures above 30°C, must be considered. The protein portion of the enzyme is inactivated and the reactiosn apparently begin to slow down at temperatures above 30° C. It is therefore obvious that, at present, a semi-empirical relationship must be used to describe the variation of the B.O.D. reaction rate with temperature. Such a relationship proposed by Streeter and Phelps (1925) and still favored by most workers is

$$k_{1(T)} = k_{1(20)}\theta^{(T-20)} \qquad \text{II-5}$$

in which $k_{1(t)}$ = the BOD rate constant at temperature T, in °C; $k_{1(20)}$ = the rate constant at 20°C; and θ= a constant, usually taken to be 1.047.

This formulation was originally expected to hold for temperatures between 2°C and 40°C. However, Gotaas (1948) showed that the maximum reaction rate is reached at about 30°C, and decreases at higher temperatures. He also found that the value of the constant, θ, is higher at lower temperatures. Both of these findings can be rationalized. The decrease in reaction rate at high temperatures could be caused by thermal inactivation of enzymes, and the high rate changes at lower temperatures could be caused by the shift from a psychrophylic to a mesophylic population predominance. Gotaas found that the variation of reaction rate with temperature could be accurately described by equation II-3, with three temperature ranges. They were

5 to 15°C $\theta = 1.109$
15 to 30°C $\theta = 1.042$
30 to 40°C $\theta = 0.967$.

For the range 5 to 30°C, the average value of θ was 1.071.

It should not be expected that the data of different workers on this subject will agree. It should be obvious, in the light of the discussion of the BOD reaction herein, that the rate of oxidation will vary with the type of waste and the type of biological population which grows in response and oxidizes the waste. Under differing conditions, different biological populations will vary in their temperature susceptibility so that temperature coefficients and temperatures of maximum reaction rates will also vary.

It should be noted that Schroepfer, et al. (1961) found different results using stabilized effluents and river waters than previously reported. Also, his work assumed that at elevated temperatures of 35°C, significant nitrification began in less than five days.

Zanoni (1967) found that BOD data at all temperatures more nearly followed a second order reaction equation and that the second order equation ultimate demands were higher than those predicated by the first order equation. He also found values for θ between 10 to 30°C similar to those of past investigations. In a subsequent study, Zanoni (1969) further substantiated past work on both the ultimate demand the the temperature constants for the carbonaceous stage. However, he reported that the nitrogenous stage demonstrated an optimum rate at 22°C and decreased until 30°C was reached. For the nitrogenous phase, he found a value of θ of 1.097 for temperatures from 10°C to 22°C, and 0.877 for temperatures from 22 C to 30°C.

Temperature also has a profound effect on the bactericidal and viruscidal activity of chlorine compounds. Butterfield and Wattie (1946) reported that a 20 degree centigrade reduction in temperature requires nine times the exposure period or 2.5 times as much chloramine to produce a 100 percent kill. In an earlier paper, Butterfield (1943) reported similar results for chlorine. Similar studies with viruses have indicated that a 10°C decrease in temperature will increase the time required for a given amount of viral destruction by chlorine by 200 to 300 percent (Clarke and Chang, 1959).

C. Chemical

An increase in temperature will usually have a profound effect on chemical reactions, the rate of reaction being approximately doubled for each 10 C rise in temperature (Glasstone, 1946). The variation of an equilibrium constant, k, may be expressed as:

$$\frac{d(\ln k)}{dT} = \frac{E_a}{RT^2} \qquad \text{II-6}$$

where

T = absolute temperature,

E_a = activation energy,

R = gas constant.

Integration of equation (II-6) between temperatures T_1 and T_2 yields:

$$\ln \frac{k_2}{k_1} = \frac{E_a(T_2-T_1)}{RT_1T_2} \qquad \text{II-7}$$

The activation energy, E_a, is a measure of the requisite energy for a molecule to take part in a reaction and for many reactions may be determined by plotting ln k against 1/T, the slope of the line being -E/R.

Other methods common to the pollution control field for expressing the temperature dependence of reaction rates are (Fair and Geyer, 1954):

$$\frac{k_2}{k_1} = H^{T_2-T_1} \quad \text{where } H = \frac{k_2}{k_1} \text{ for } T_2-T_1 = 1 \qquad \text{II-8}$$

and:

$$Q_{10} = \frac{k_2}{k_1} \text{ for } T_2 - T_1 = 10 \qquad \text{II-9}$$

It should be noted that T_2 and T_1 are measured in degrees Centigrade for equations II-6 and II-7 and that Q_{10} and H vary with temperature. It is also of interest to note that $Q_{10} = H^{10}$.

Temperature affects not only the rate at which a reaction occurs, but the extend to which the reaction takes place. When considering temperature changes in a receiving water, one must contemplate changes in ionic strength, conductivity, dissociation, solubility and corrosion. With an increase in temperature, these changes might very well result in differing chemical requirements in the water treatment plant.

D. Research Needs

1. With the exception of the reaeration process, the effects of temperature on physical water quality parameters are fairly well established. Even in the reaeration process, empirical coefficients allow fairly accurate prediction of temperature effects. From the academic standpoint, it would be informative to obtain further substantiation of the empirical coefficients and a rational insight into their origin. It might also be well to determine the costs associated with this and other physical parameters that change with temperature. For example, what are the economic implications of the chan ges in temperature of filtration, sedimentation and ion-exchange?

2. Probably the most pressing need for research in the biological aspects of this chapter are with regard to the effect of changes in temperature on the deoxygenation rate. It would be most useful to know the mechanism and the quantitative effects of increased temperatures on the stabilization process when the temperatures exceed 30°C.

It would also be useful to know more about the relationship between temperature and nitrification. The application of first or second order kinetics to the B.O.D. phenomena might well be elucidated. Because of the apparent profound effects of temperature on the disinfection process, further quantitative data on this aspect would appear desirable.

3. As with the physical processes, the effects of temperature on chemical parameters are fairly well established. However, it would be useful to know the economic implications of changes in temperature on such parameters as ionic strength, conductivity, dissociation, solubility, and corrosion.

Bibliography

Baumeister, T., and Marquardt, D. W., 1964, "Least Squares Estimation of Nonlinear Parameters". Share Distribution Number 1428 DFE 2135 (PA), Share General Program Library.

Butterfield, C. T., Wattie, E., Megregian, S., Chambers, C. W., 1943, "Influence of pH and Temperature on the Survival of Coliform and Enteria Pathogeus when Exposed to Tree Chlorine", Public Health Reports, Vol. 59.

Butterfield, C. T., and Wattie, E., 1946, "Influence of pH and Temperature on the Survival of Coliforms and Enteric Pathogens When Exposed to Chloramines", Public Health Reports.

Churchill, M. S., Elmore, H. L., and Buckingham, R. A., 1962, "The Prediction of Stream Reaeration Rates", Journal of the Sanitary Engineering Division, ASCE, Vol. 88, SA4, Proc. Paper 3199.

Clarke, N. A., and Chang, S. L., 1959, "Enteric Viruses in Water", Journal of the American Water Works Association, 51, 1310.

Dobbins, W. E., 1964, "BOD and Oxygen Relationships in Streams", Journal of the Sanitary Engineering Division, ASCE, Vol. 90, SA3, Proc. Paper 3949, pp. 53-78.

Fair, G. M. and Geyer, J. C., 1954, "Water Supply and Wastewater Disposal", John Wiley and Sons, New York, N. Y.

Glasstone, S., 1946, "A Textbook of Physical Chemistry", Van Nostrand, New York, N. Y., 1087.

Gotaas, H. B., 1948, "Effect of Temperature on Biochemical Oxidation of Sewage", Sewage Works Journal.

Gunter, G., 1957, "Temperature in Marine Ecology and Paleoecology", Geol. Society of America.

Krenkel, P. A., and Orlob, G. T., 1963, "Turbulent Diffusion and Reaeration Coefficient", Transactions, ASCE, 128.

Marquardt, D. W., 1963, "An Algorithm for Least Squares Estimation of the Non-Linear Parameters", Journal of the Society for Industrial and Applied Mathematics.

McKee, J. E., and Wolf, H. W., 1963, "Water Quality Criteria", State Water Control Board, Sacramento, Calif.

O'Connor, D. J., and Dobbins, W. E., 1958, "Mechanisms of Reaeration in Natural Streams, *Transactions, ASCE*.

Schroepfer, G. J., 1961, *Pollution and Recovery Characteristics of the Mississippi River*, Vol. I, Part III, report by Sanitary Engineering Division, Department of Civil Engineering, University of Minnesota.

Streeter, H. W., and Phelps, E. B., 1925, "A Study of the Pollution and Natural Purification of the Ohio River", Public Health Service, U. S. Government Printing Office, Washington, D. C., Bulletin 146.

Thackston, E. L., Hays, J. R., and Krenkel, P. A., 1967, "Least Squares Estimation of Mixing Coefficients", *Journal of the Sanitary Engineering Division*, ASCE, Vol. 93, No. SA3, Proc. Paper 5288.

Thackston, E. L., and Krenkel, P. A., 1966, "Longitudinal Mixing and Reaeration in Natural Streams," *Technical Report No. 7*, Sanitary and Water Resources Engineering, Vanderbilt University.

Zanoni, A. E., 1967, "Waste Water Deoxygenation at Different Temperatures", *Water Research*.

Zanoni, A. E., 1969, "Deoxygenation and Temperature", *Journal Water Poll. Control Fed.*, 656.

CHAPTER III -/

EFFECTS OF TEMPERATURE ON AQUATIC ORGANISMS

The effects of temperature upon aquatic organisms have always been of great interest to biologists and much research has been carried out in this area since the late 1880's. This research has been the subject of a number of comprehensive literature reviews (Brett, 1956; Gunter, 1957; Wurtz and Renn, 1964; Mackenthum, 1967; De Silva, 1969; Hokanson, 1969) and bibliographies (Trembly, 1960; Kennedy and Mihursky, 1967; Raney and Menzel, 1967).

Unfortunately, the sheer mass of detailed information in these reviews leaves the reader with a feeling of hopeless frustration. The possibility of organizing this wealth of information into a useful form which will permit a logical approach to evaluation and control appears rather dim. At the Portland Seminar on Thermal Pollution, Strickland (1968) reflected this mood of frustration and gloom when he commented, "Really, the business is in such a state that we can never be certain. We don't really know to what extent the entire food chain and its indirections and feedbacks are affecting any particular part of it. The more we get to know about it, the more complicated and inter-acting it becomes."

The present authors believe that one reason for this understandable despair lies in the attempts to cover all the various ramifications of temperature effects upon the aquatic environment in a single paper or review. Therefore, in the present survey the authors will largely restrict their efforts to a consideration of the effects of heated discharges upon freshwater ecosystems.

Of course, many of the useful principles enunciated herein will be applicable to estuarine and marine systems. As stated by deSylva (1969), the marine fishes are more exacting in their requirements than brackish water or freshwater species, but their basic life histories are quite similar. The effects of temperature on the Pacific salmon, a species of particular importance to U. S. Fisheries, is considered in detail in Appendix A .

Recognizing with Strickland the complexities of the interactions of the numerous environmental conditions affecting aquatic communities and the incompleteness of our knowledge of these interactions; and with Hynes (1960) that "the final answer as to how much of any particular poison can be tolerated by a population of fishes living a natural life in a river still remains unanswered except where it is based on field observations;" the authors decided that, under the circumstances, the empirical approach would probably be most profitable, i.e., temperature effects upon aquatic biota in situ. Therefore, while not ignoring laboratory results, this survey places major emphasis on the results of field studies made in operational situations.

A. Known Effects of Temperature

The response of aquatic organisms to elevated water temperatures has been studied in the laboratory and in situ by experts in many scientific disciplines. These responses have been described in the review articles cited above. Another complete review of the literature would be redundant; however, some well documented responses of primary significance must be recounted.

Those well documented responses are:

1. A shift in population structure of the ecosystem:

The structure of aquatic communities, often called the "food web" (Fig. III-1) is the result of the relationship between organisms and the environment as well as among the organisms themselves. Most forms of stress cause a decrease in the complexity of the aquatic community (Cairns, 1967).

Patrick (1949) demonstrated the effects of organic pollution on population diversity by comparing the total number of species in each of seven taxonomic groups with the number in that group at stations relatively free of pollution. Typical results for various degrees of pollution are shown in Figure III-2, with the related taxonomic grouping of organisms and interpretation of results in Table III-1. 1. Patrick et al.(1954) also examined the effects of pollution on the diversity of the diatom population. Diversity-density distribution plots for an unpolluted stream and for a polluted one appear in Figure III-3.

The above examples indicate that a healthy aquatic community is one in which many species are present, with each species having few individuals; while under stressed conditions, fewer species are present with large numbers of individuals per species.

The effect of temperature on population structure can best be illustrated with a mixed algae population which is subjected to a gradual increase in temperature. Figure III-4 demonstrates the shift in predominance from diatoms at 20°C to blue green algae, the species often found in abundance under conditions of organic or chemical

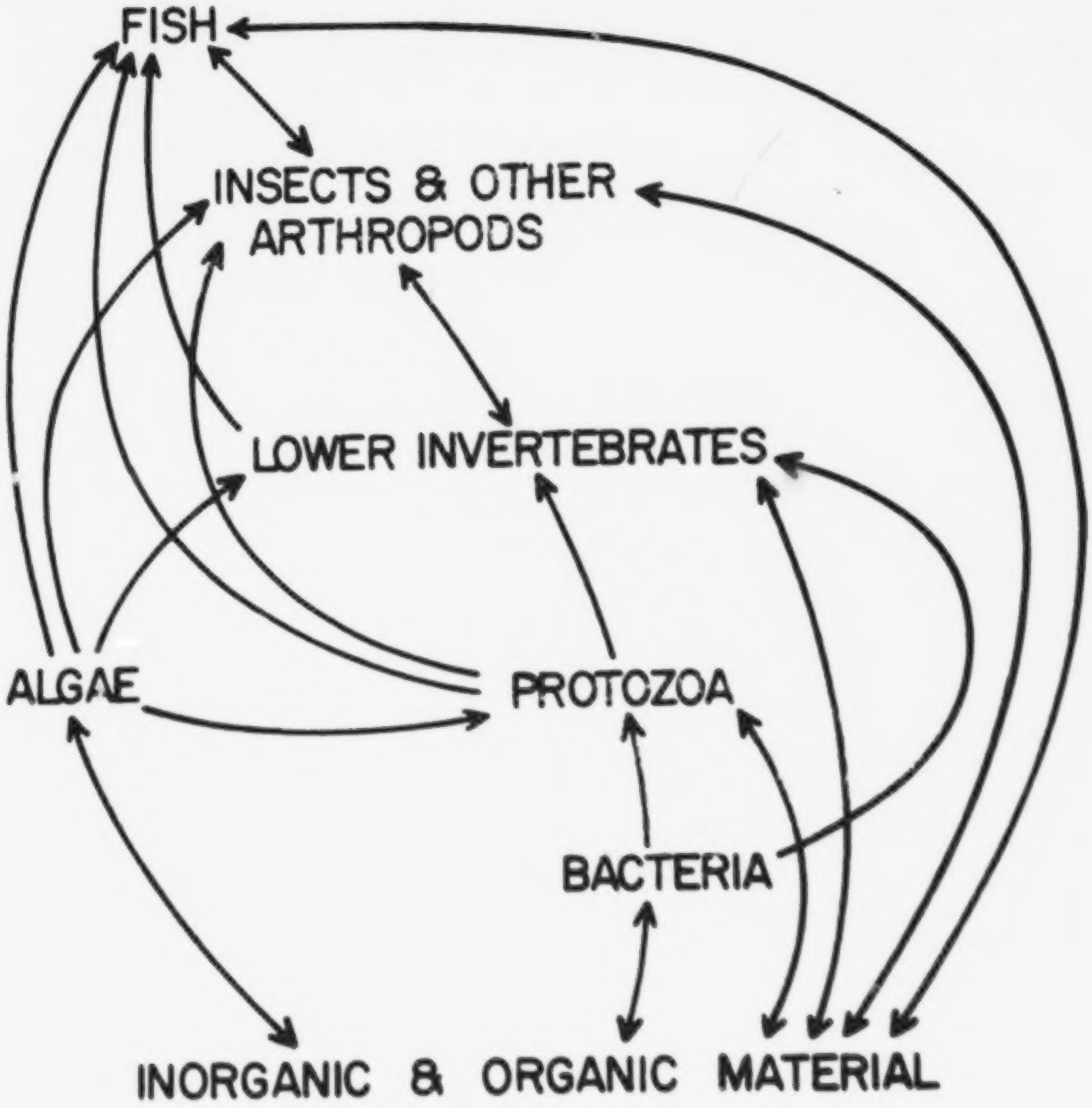

FISH
INSECTS & OTHER ARTHROPODS
LOWER INVERTEBRATES
ALGAE
PROTOZOA
BACTERIA
INORGANIC & ORGANIC MATERIAL

FIGURE III - 1 SIMPLIFIED AQUATIC FOOD WEB

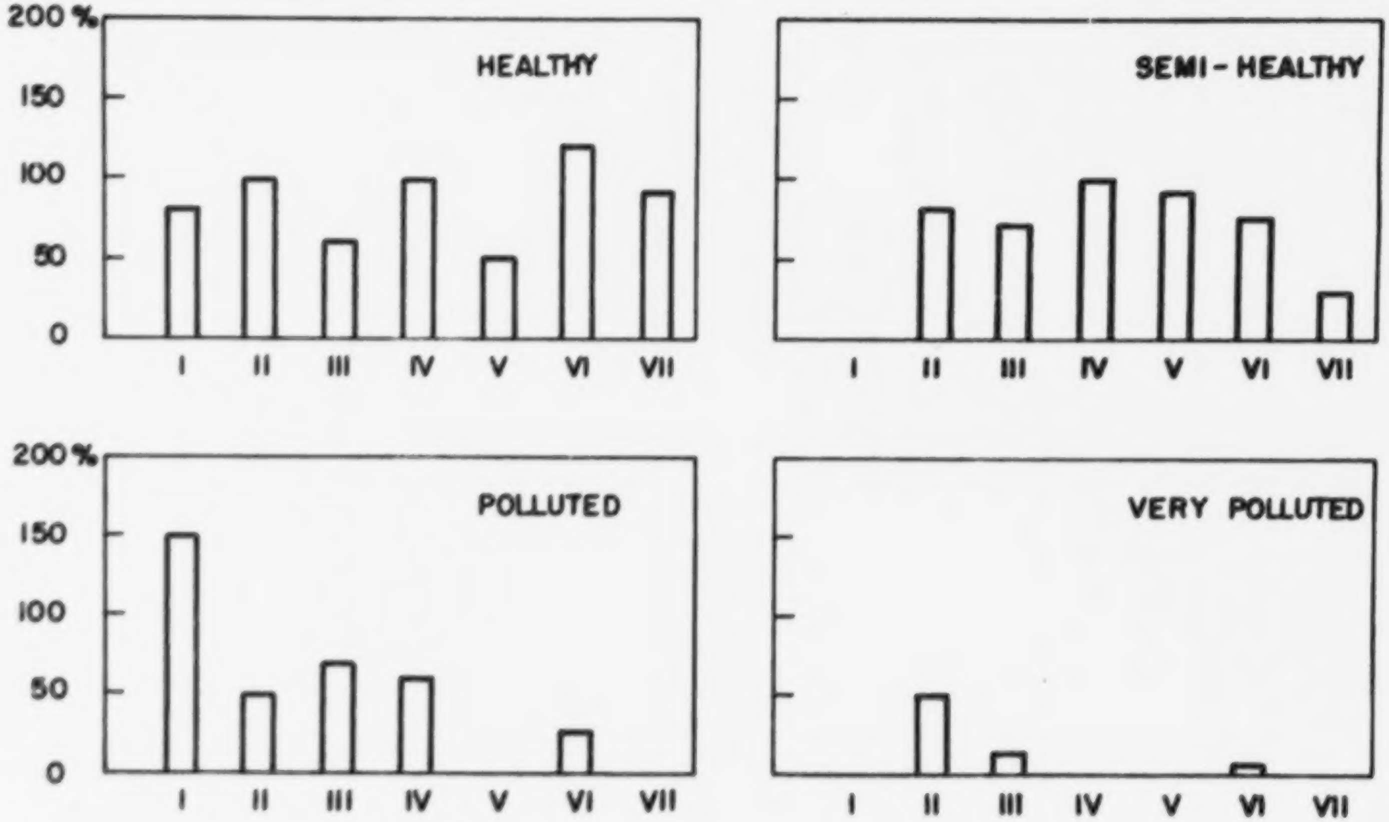


FIGURE III - 2 TYPICAL HISTOGPAMS OF VARIOUS DEGREES OF POLLUTION

TABLE III-1

TAXONOMIC GROUPING OF ORGANISMS AND INTERPRETATION OF RESULTS OF PATRICK'S SYSTEM OF BIOLOGICAL MEASUREMENT OF STREAM CONDITION

Column	Organisms
I	The blue-green algae, Stigeoclonium, Spirogyra, Tribonema, and certain rotifers
II	Oligochaetes, leeches and pulmonate snails
III	Protozoa
IV	Diatoms, red algae, and most green algae
V	All rotifers not included in I plus clams, prosobranch snails and tricladid worms
VI	All insects and crustacea
VII	All fish

Stream Conditions	Results
Healthy	Col. IV, VI and VII all above 50 per cent
Semi-Healthy	(a) Either or both Col. VI or VII below 50 per cent and Col. I or II under 100 per cent, or (b) Either Col. VI or VII below 50 per cent, and Col. I, II and IV 100 per cent or over, or Col. IV is double width
Polluted	(a) If either or both of Col. VI and VII are absent, and Col. I and II are 50 per cent or better, or (b) If Col. VI and VII are both present, but below 50 per cent then Col. I and II must be 100 per cent or more
Very polluted	(a) If Col. VI and VII are absent and Col. IV is below 50 per cent, or (b) If Col. VI or VII is present, but Col. I or II is less than 50 per cent

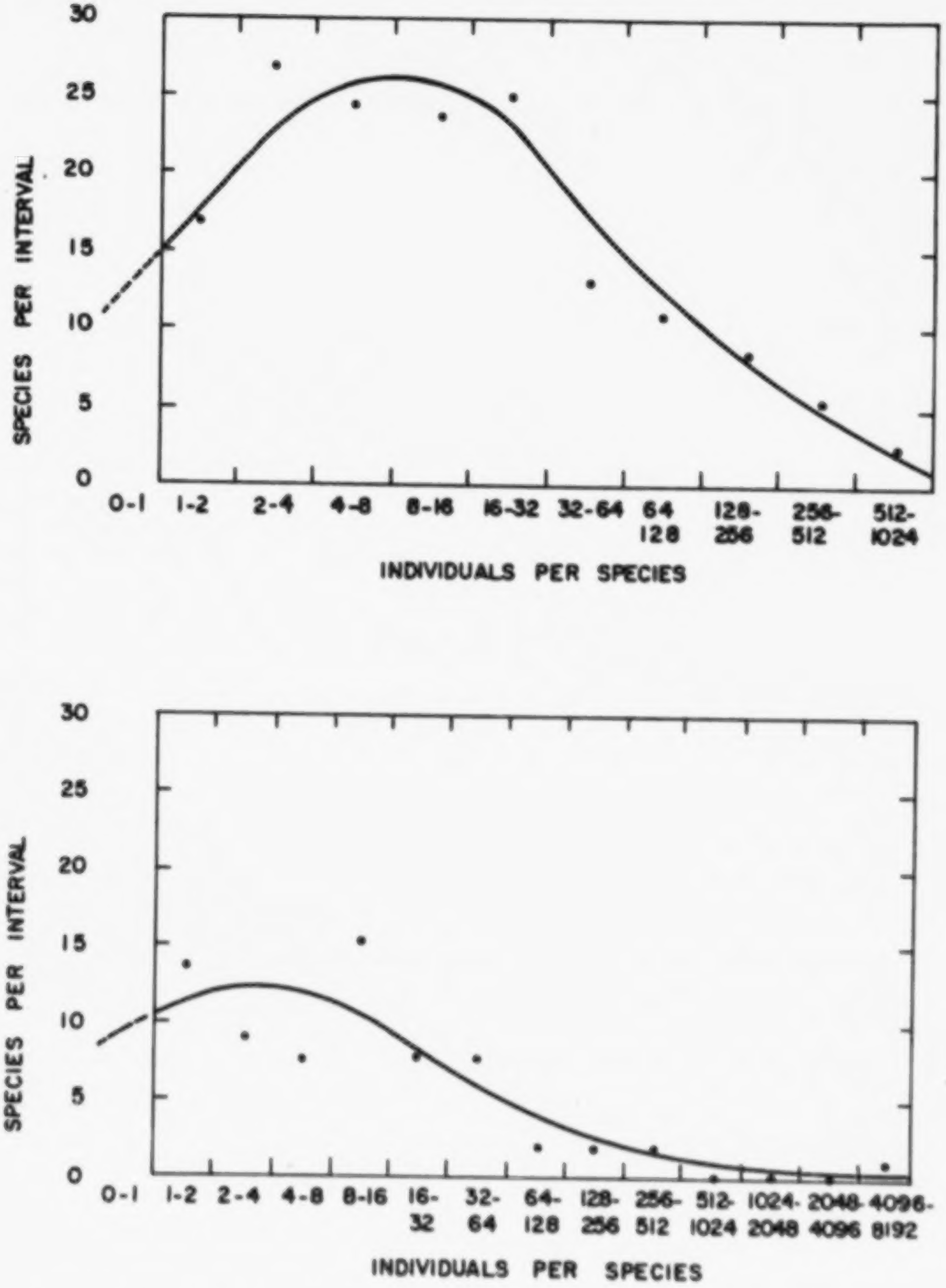


FIGURE III - 3 DIVERSITY-DENSITY DISTRIBUTION FOR UNPOLLUTED (UPPER CURVE) AND POLLUTED (LOWER CURVE) STREAMS

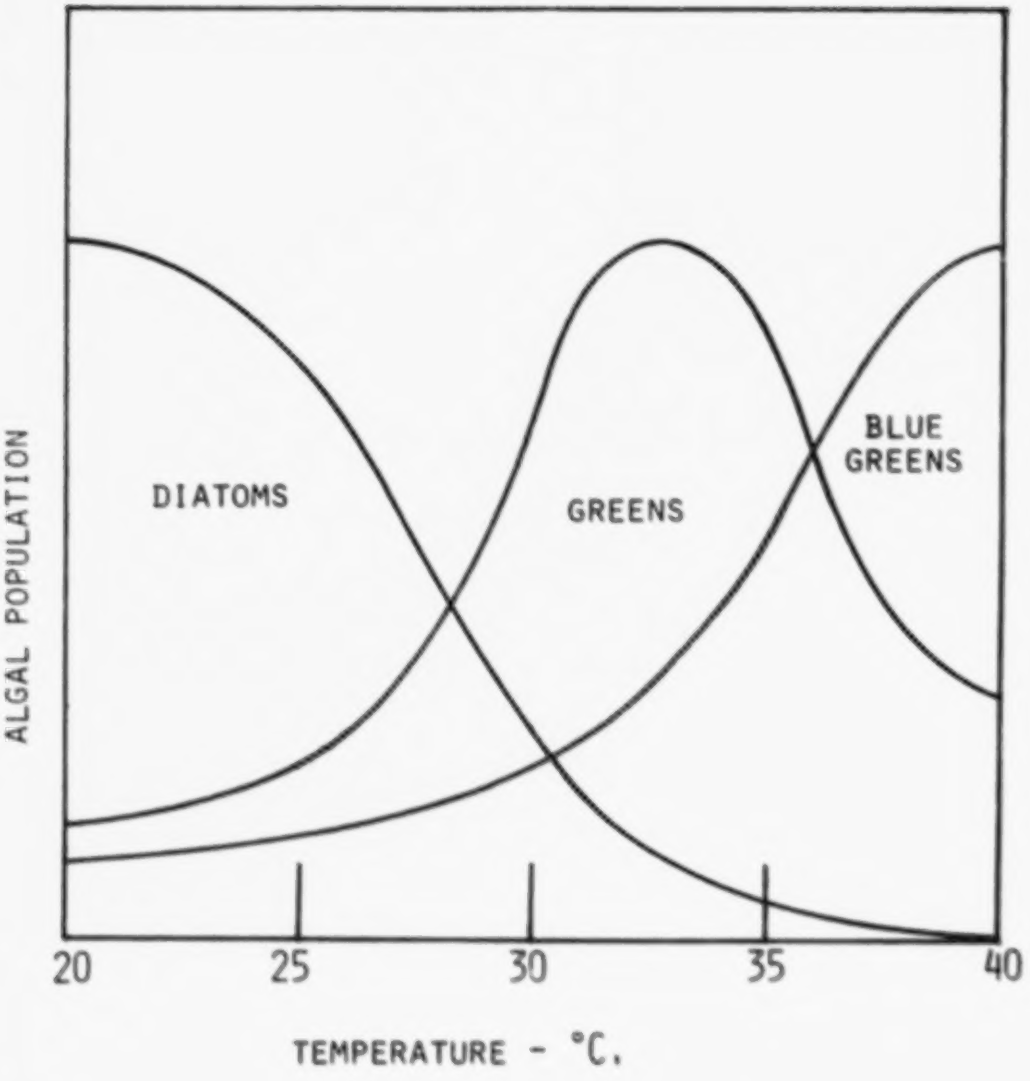


FIGURE III - 4 ALGAE POPULATION SHIFTS WITH CHANGE IN TEMPERATURE

pollution, in the range of 35 to 40 C. (Cairns, 1956).

Wurtz and Dolan (1960) concluded from the results of a study on a stretch of the Schuylkill River into which heated water was discharged that the hot-water discharge reduced the diversity of the prevailing biological structure of the river.

2. Death beyond certain temperatures:

Extremes of temperature which can be endured by fishes have been studied since the 1940's (Brett, 1960), with considerably more emphasis on upper lethal temperatures than on lower ones. Comprehensive tables o of lethal temperatures and the associated acclimatization temperatures for a large number of species have been compiled by Jones (1964), McKee and Wolf (1962), Mason (1963), FWPCA (1967), and de Sylva (1969).

The lethal temperature has been found to be a function of many factors including diet, activity, age, general health, osmotic stress, and weather. This large number of variables makes it difficult to determine a useful value for the lethal temperature under laboratory conditions since the lethal temperature changes somewhat with variations in each of those variables.

However, the aquatic species, its thermal history, and the exposure time are major factors which affect lethal temperature levels.

The tables mentioned above demonstrate the variety of thermal limits among the fishes. Brett (1952) demonstrated the variance of these limits among seven species acclimated to the same temperature using data from three authors (Figure III-5). In the same figure, the effect of exposure time on the upper lethal limit for each of the species is shown. The fact that the semi-logarithmic plots of temperature versus time to 50% mortality are reasonably parallel is noteworthy.

The effect of acclimatization (thermal history) and exposure time on upper lethal limits for a single species is shown in Figure III-6.

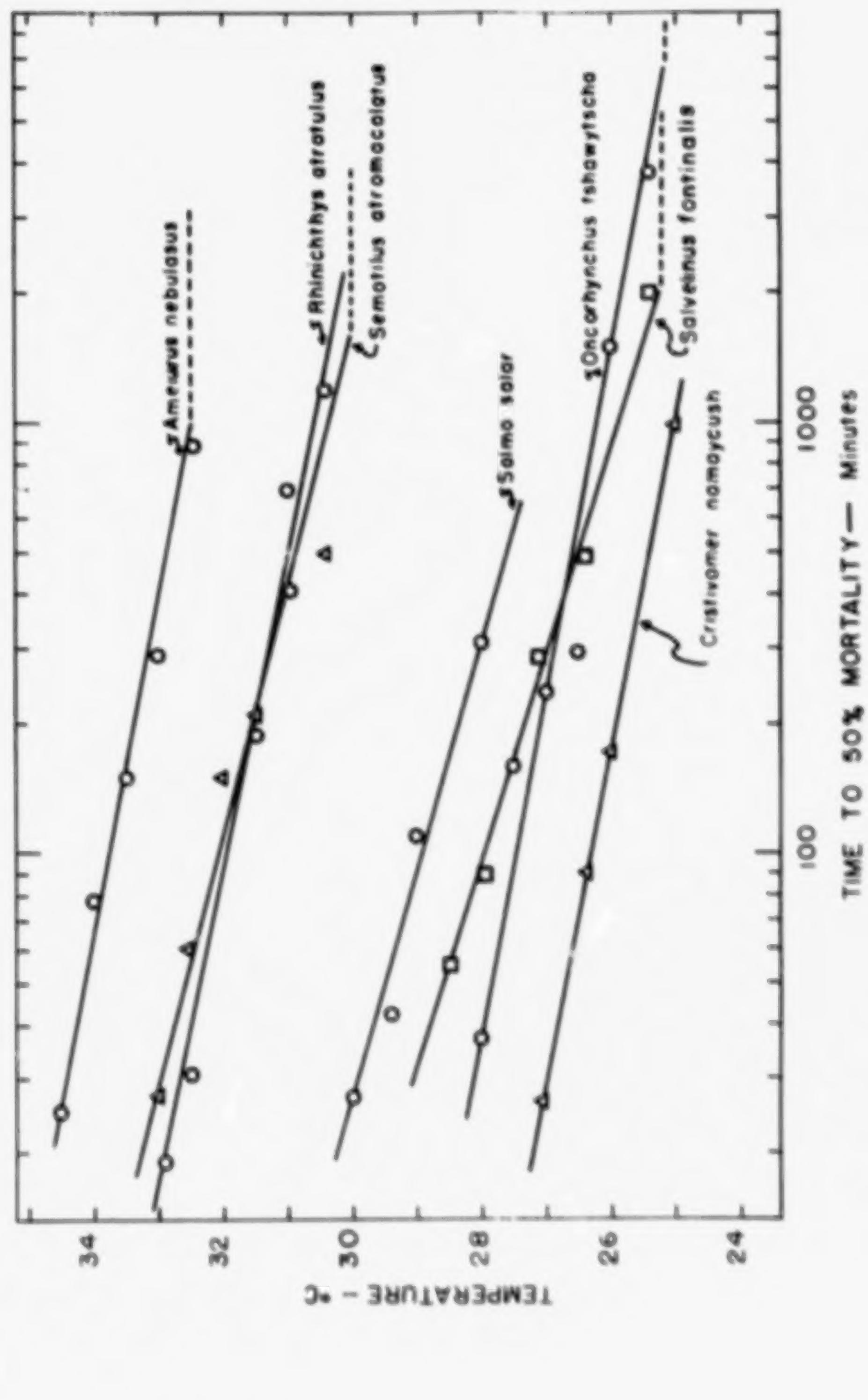


FIGURE III - 5 MEDIAN RESISTANCE TIMES FOR FISH ACCLIMATED TO 20°C

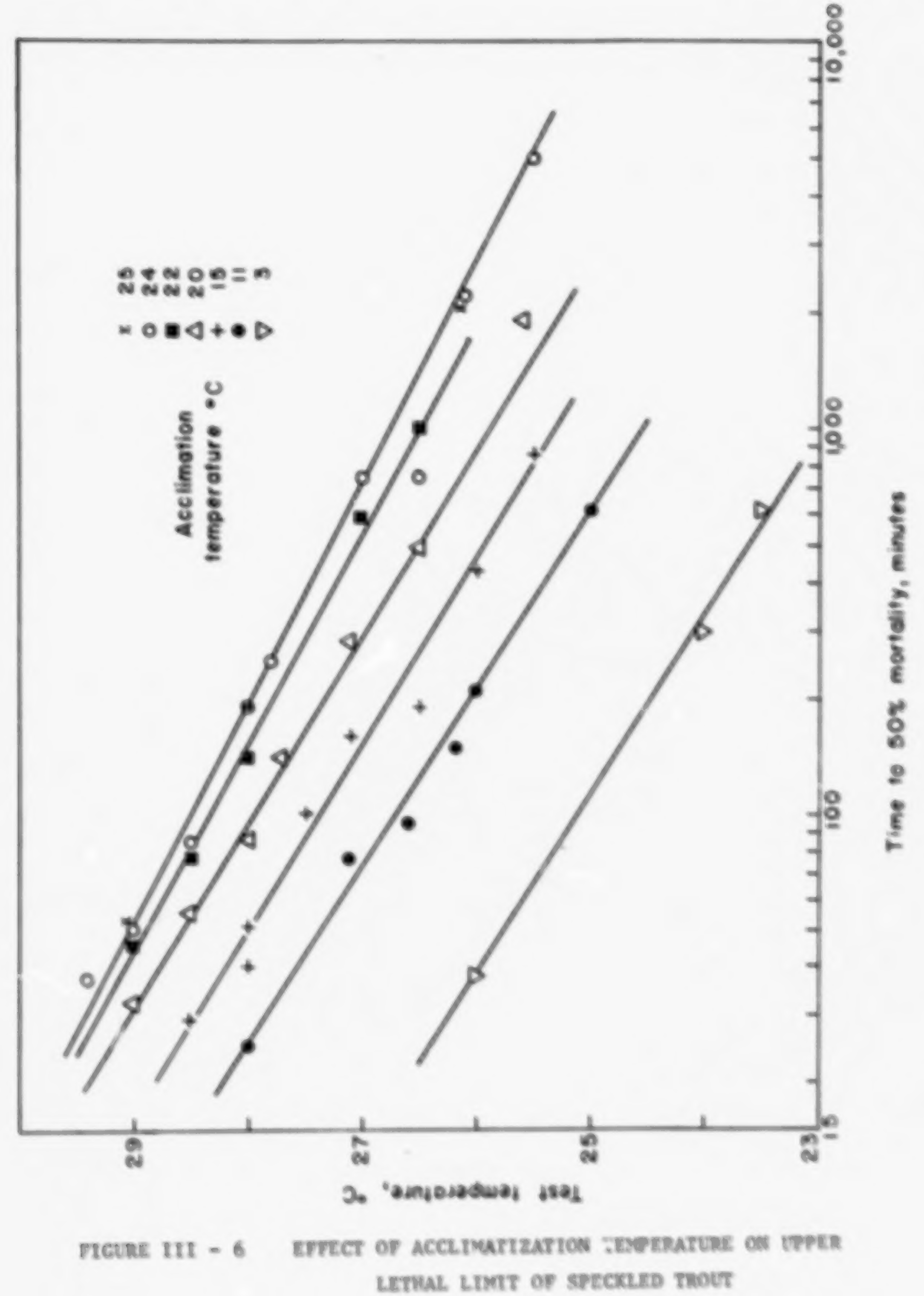


FIGURE III - 6 EFFECT OF ACCLIMATIZATION TEMPERATURE ON UPPER LETHAL LIMIT OF SPECKLED TROUT

The extremes of temperature which can be tolerated indefinitely by a species and their dependence on acclimatization temperature can be summarized in a "tolerance trapezium" similar to Brett's (1960), which appears in Figure III-7. It is significant that the difference between the 50%- and the 5%-lethal levels is small, indicating that a large increase in mortality can result from a small change in temperature near the tolerance limits (Brett, 1958).

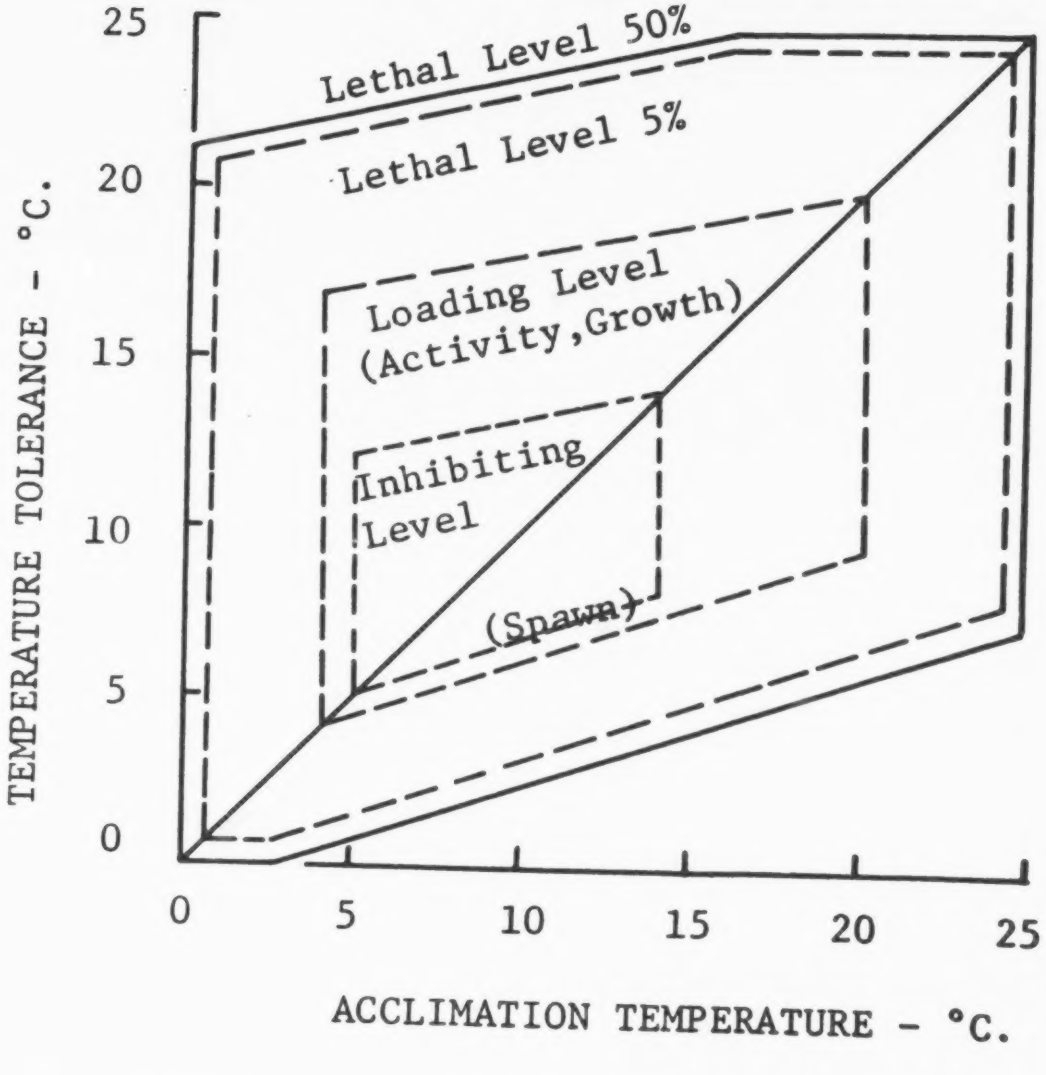


FIGURE III - 7 UPPER AND LOWER LETHAL TEMPERATURES FOR YOUNG SOCKEYE SALMON

3. Sublethal functional response

Extreme temperature is a killer, of course; but within the zone of tolerance temperature is a catalyst, a depressant, an activator, a restrictor, a stimulator, a controller. Temperature is one of the most important and influential water quality characteristics to life in water (Federal Water Pollution Control Administration, 1967).

De Sylva (1969) summarized the effects of temperature on metabolism, respiration, behavior, distribution and migration, feeding rate, growth and reproduction as well as parasites and diseases in fishes; and a similar review is unnecessary.

Brett (1960) recognized the limiting capability of temperature on fishes when he produced the "tolerance trapezium" (Figure III-7). Well within the zone of tolerance lies a smaller zone outside which activity and growth are limited. Within that zone lies an even smaller one which defines the temperatures which allow normal reproduction. Although the boundaries of the smaller zones are not as well defined as those of the tolerance zone, their significance is recognized.

The relationship between rate of metabolism and temperature for two species is shown in Figures III-8 and III-10 (Fry and Hart, 1948). The difference between active metabolic rate and standard rate is called the scope of activity (Graham, 1949). Figure III-9 demonstrates the similarity between the graphs of cruising speed of the goldfish versus temperature and scope of activity versus temperature.

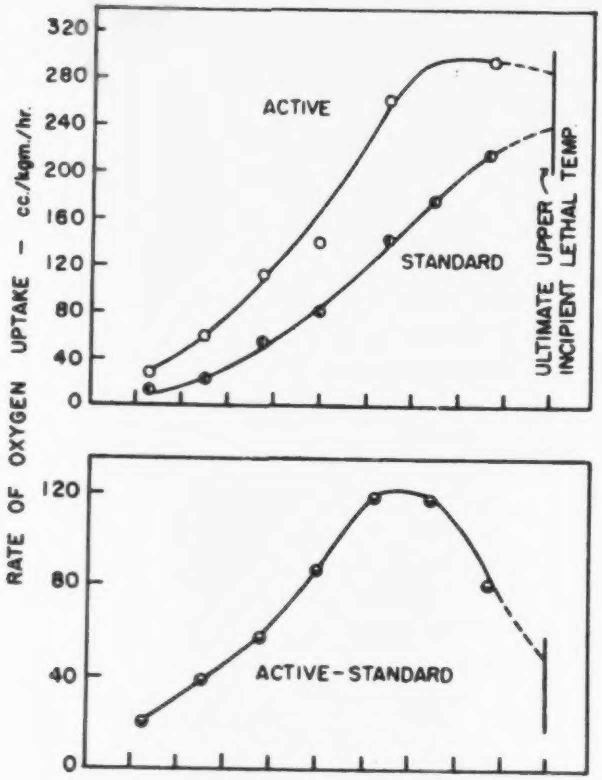


FIGURE III - 8 RELATIONSHIP BETWEEN TEMPERATURE AND ACTIVE AND STANDARD LEVELS OF OXYGEN UPTAKE

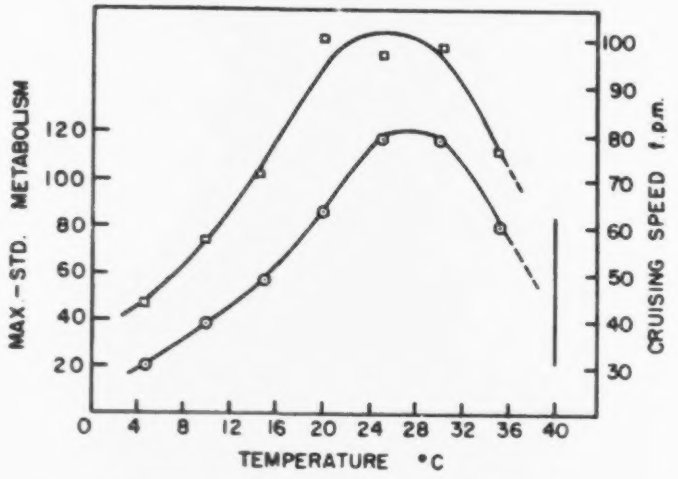


FIGURE III - 9 DIFFERENCE BETWEEN MAXIMUM AND STANDARD LEVELS OF OXYGEN UPTAKE (LOWER CURVE) AND SPEED AT WHICH GOLDFISH CAN SWIM STEADILY AT VARIOUS TEMPERATURES

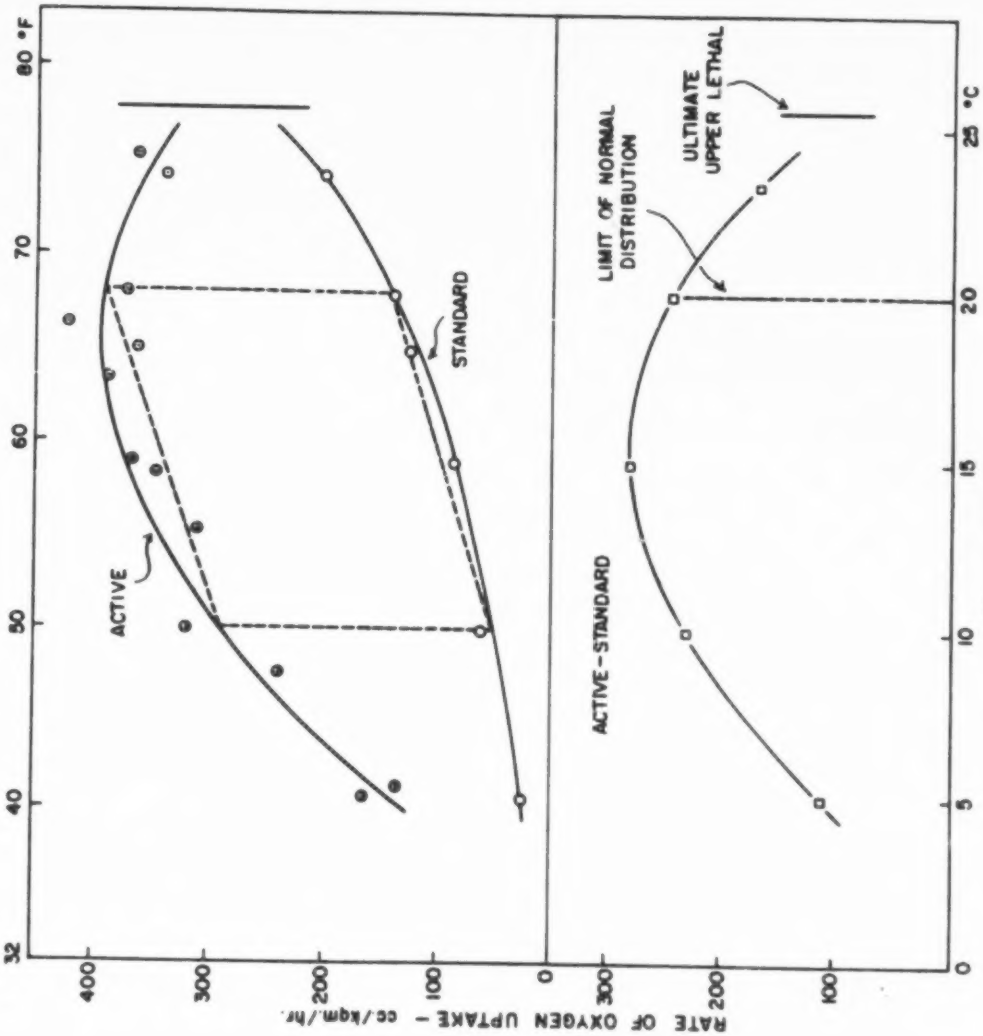


FIGURE III - 10 RELATION OF OXYGEN UPTAKE TO TEMPERATURE IN ACCLIMATED SPECKLED TROUT

4. Decreased resistance to toxic substances:

Although literature on fish toxicology is voluminous and excellent summaries of published data are available (Doudoroff, 1957) the specific effects of temperature on the toxicity of many pollutants are not well documented. De Sylva (1969) has summarized the available data on the combined and synergistic effects of heat and toxic materials on fish.

Generally, two conclusions can be drawn from existing data. Toxicity usually increases with increased temperature, and specimens subjected to toxic materials are less tolerant of temperature extremes. Since chemical reaction rates increase with increased temperature and metabolic rates generally increase at higher temperatures, these results should be expected. This general rule is not without exception, however. For example, Brown, et al.(1967) found that resistance to poisoning by phenol increased in the rainbow trout with an increase in temperature, to temperatures as high as 18°C.

B. Recorded Thermal Fish Kills

It is pertinent to determine just what the record is in terms of fish kills caused by heat additions. At the very outset, however, the authors recognized with Mount (1969) that many field observations regarding the well-being of species are sometimes erroneous. Thermal stratification sometimes is overlooked and fish are reported to be living at very high temperatures when in fact the surface layer is at that temperature while the fish are actually at a level where water is considerably cooler.

Gunther (1936) stated that heavy mortality in marine fishes and invertebrates occurred during the sporadic appearance of the Equatorial Countercurrent which averages about 7°C. higher than normal ocean waters. All the fish in a small pond near Savannah, Georgia, were killed when the water temperature reached 108°F. (Tarzwell, 1956).

In a study of lake stocking techniques, Threinen (1958) observed mortalities in rainbow trout at surface temperatures of 74°F., well below the reported lethal limits. He discovered, however, that death resulted from the instantaneous rise in environmental temperature which occurred when the trout were transferred from 54°F. water in a tank truck to the 79°F. lake water. Mortalities were reduced or eliminated by gradually raising the temperature (over a 24-hour period) to that of the lake, or by lowering the fish in live boxes to a cooler level of the lake.

Clark (1969) described several fish kills attributed to heated discharges. These incidents were produced by exceptional circumstances. The first case occurred in 1963 at a nuclear power plant on the Hudson River. The wintering striped bass were attracted to the warm water coming from the plant, became trapped near the discharge, and died by the thousands. Another kill occurred during testing operations at a new power plant on the Cape Cod Canal in the summer of 1968 when a large number of menhaden were trapped in a 93-95° F effluent from the plant. The details of the trappings were not given in Clark's account.

Alabaster (1963) reported a kill of about a hundred gudgeon and roach at Castle Donington power station in 1959 and several hundred gudgeon at Goldington in 1958. Each case illustrates the highly lethal effect of a sharp increase in temperature - in these incidents, 5-6° C in 2-3 hours. In each case, most of the dead fish were small, suggesting that the larger fish moved away from the outflow to avoid unpleasant conditions there.

Using nine species of fish, Nickum (1967) investigated maximum sudden change in temperature which would allow all the fish in a test population to survive. Provided the temperature did not exceed the lethal limit for the particular species, sudden changes up to 20° F produced little behavioral reaction and no immediate mortality, but sudden changes exceeding 20° F often caused mortality. Nickum noted increased sensitivity to sudden changes in temperature during the spring and early summer.

It should be noted that organisms are also quite sensitive to changes in temperature caused by cooler water. For example, Jones (1966) has reported several fish kills in the TVA region caused by the release of cold, oxygen devoid waters from the hypolimnion released from Fort Loudon Dam in Tennessee.

In what may be the first case of an indemnity payment for fish killed specifically by thermal pollution, the Northern Ohio Sugar

Company recently paid $3,241.09 to the Ohio Department of Natural Resources. According to State Wildlife Division Chief Daniel C. Armbruster, hot water discharged by the sugar processing plant at Fremont, Ohio on the Sandusky River, resulted in losses of fish during January, 1967, and again in January, 1968.

Thoman (1969) has reported extensive damage to the ecosystem of Biscayne Bay caused by the release of heated water from the power plant, although a formal report has not yet been released.

Actually, in the literature there is a surprising scarcity of fish kills in which the lethal agent is incontestably heat addition. Information on reported thermal-caused fish kills was presented to the Congress by FWPCA Deputy Commissioner John Barnhill and summarized in the Sport Fishing Institute Bulletin as shown in Table III-2.

C. Protective Responses in Aquatic Organisms

Several characteristics of biological life seem particularly pertinent in evaluating the magnitude of the thermal pollution problem and devising methods of control. These characteristics are:

(a) Heat tolerance range

(b) Ability to acclimate to changes in the ambient environment

(c) Avoidance reactions

It will be seen that heat discharged into the aquatic environment becomes a problem only when these protective mechanisms are overwhelmed.

Adaptability is fundamental to biological life. The term means a response by the organism to some alteration in the environment, allowing the organism to survive under the changed conditions.

TABLE III-2

KNOWN INSTANCES OF THERMAL-CAUSED FISH KILLS AS REPORTED TO CONGRESS MAY 17, 1968

Date	Location	No. Fish Killed
Aug 6-8, '62	Raystown Br., Juniati River (Nr. Saxton, Pa.)	3,441
Aug 11, '62	Discharge Can. to Montrose L. (Nr. Ladue, Mo.)	"Several thousand"
Sep 7, '63	Rock River (Nr. Rockford, Ill.)	"Several thousand"
May 28, '64	Unnamed Stream (Nr. Victoria, Texas)	"Several thousand"
Aug 19, '65	Schuylkill River (Nr. Reading, Pa.)	1,000
Aug 20, '65	Greater Miami River (Nr. Montgomery Cty, Ohio)	11,250
Jan 19-22, '66	Ohio River (Nr. Toronto, Ohio)	200
Sep 2, '66	Schuylkill River (Nr. Philadelphia, Pa.)	50,000
Jan 1, '67	Sandusky River (Nr. Sandusky Cty, Ohio)	300,385
Jan 17, '67	Sandusky Bay (Nr. Erie Cty, Ohio)	68,750

The adaptability of an organism depends upon its genotype (genetic individuality) and its phenotype (phenotypic plasticity). Genetic individuality refers to the range of adjustments possible to that organism as determined by its gene or hereditary background. By phenotypic plasticity is meant the ease with which the organism make the adjustments permitted by genetic individuality.

Any organism is a regulator. In the face of applied stress, it attempts to maintain a steady state in its internal environment. Basically, maintaining this steady state means keeping the vital activities of the internal environment fluctuating about some mean value within the range of allowable, nondestructive variability set by the genotype.

This regulation may be accomplished internally or externally. The process of internal regulation is manifested in heat tolerance and in acclimation. Temperature selection is a type of external regulation.

Animals fall into two general groups, the homoiotherms (warm-blooded) and poikilotherms (cold-blooded). The warm-blooded animals, such as birds and mammals, have well-developed temperature-regulating mechanisms which keep the body in a very narrow temperature range, regardless of the ambient environment. The lower vertebrates and the invertebrates are poikilothermic, i.e., their body temperature follows that of the surrounding environment. In other words, in the poikilotherms, body temperature is not regulated. However, regulation must occur in some other physiological function of the organism. The nature of the regulatory mechanism has been studied (Troshin, 1967) but will not be discussed in this report.

D. Heat Tolerance in Organisms

The zone of temperature tolerance for fishes and its dependence on primary environmental parameters has already been discussed in detail. Generally, those principles apply to all aquatic poikilotherms, although more specific information is available on fish than on other biota.

The thermal tolerance of a particular species is, in all probability, the factor which limits that species to a particular area (Mount, 1969), since at the southern extremity of the range of the species, natural temperatures frequently approach lethal limits.

According to Usinger (1956), the heat tolerance of macroscopic invertebrates is well above that of fish. For example, soldier fly (Stratiomyidae) larvae were found living in thermal waters at temperatures up to 120° F. Agersborg (1932) observed a freshwater snail, *Physa gyrina*, living and reproducing nicely in zones up to 91.4° F in a ditch carrying heated waste water. Hutchison (1947) reported that *Viviparous malleatus*, a freshwater snail, was not killed until the temperature reached 37.5° C (99° F).

Several snails, including *Australorbis glabratus*, suffered heat damage at 105.8° F (Von Brand, et al., 1948). The limpet, *Ancylus fluviatilus*, was not hurt by a temperature of 96.8° F, while 87.8° F was lethal to *Acrolexus lacustris* (Berg, 1952). Wurtz's (1961) study of a river location below a heated discharge demonstrated a resident population of 19 macro-invertebrate species, even though the water temperature was at or above 95° F on 33 days, at or above 100° F for 13 days, and one day had the extreme temperature of 106.5° F.

When an unidentified species of crayfish was acclimated to 45° F, it had a lethal temperature of 93°F. (Trembley, 1961). Sprague (1963) reported a 24-hour lethal temperature of 94.3°F. for a freshwater sowbug, Asellus intermedius, and a scud, Gammarus fasciatus. Another scud, Hyalella azteca, was killed at 91.8°F. Battalgia and Lazzaretto (1967) in a study of the copepod, Tisbe reticulata, obtained data which suggested that water temperature may act to select out the more heat tolerant genotypes.

Mount (1969) said that there is a substantial amount of evidence that fish frequently are more sensitive to elevated temperatures than are most food web organisms. If this is true, then fish may serve as indicator organisms for the lethal effects of harmful agencies upon the macro-invertebrate population.

As McKee and Wolf (1963) remind us, tolerance to any potentially harmful agent is a function of the time-concentration (or intensity) relationship. Thus, an organism may survive a 10-minute exposure to 200 mg/l of a certain chemical followed by return to clean water, yet may succumb to a continuous exposure over a period of an hour to only 20 mg/l of the same substance. Of course, a temperature that kills half the fish in a given section of river in 100 minutes or 100 hours is entirely unsatisfactory. Yet, it must be realized that a certain finite period of time must elapse before a fish is killed at a certain temperature, thereby allowing the fish a period of grace during which he may make his escape into safe waters.

E. Acclimation of Organisms

Fortunately, the upper limit of the heat tolerance range is not an unalterably fixed point, since most organisms can be trained to live at higher temperatures (up to a certain limit) by intermittent or gradual exposure to temperatures higher than those of the environment in which they are presently living. This training process is called acclimation or acclimatization. Bullock (1955) has reviewed the subject of physiological compensation for temperature changes in the poikilotherms. In general, young animals are more easily acclimated than more mature animals (Shelford, 1929). Acclimation to the higher temperatures can last for some time after return of the organisms to an environment at a lower temperature.

Temperature acclimation of animals has been known for many years. In 1895, Davenport and Castle acclimated toad tadpoles to 24-25°C for four weeks while controls were held at 15°C. The temperature necessary to produce heat rigor was 3.2°C higher in the acclimated tadpoles than in the controls. Loeb and Wasteneys (1912) investigated the minimum time required to hold *Fundulus* at 27°C in order to render the fish "immune" to sudden transfer to 35°C. All fish held at 27°C for 44 hours survived transfer to 35°C, but fish held for only 21 hours suffered some mortality. These workers also learned that acclimation did not require continuous exposure to 27°C; intermittent exposure to that temperature for a number of hours each day brought about the same effect.

Many examples of laboratory acclimation of fish are found in the literature. Only a few will be cited. Fry, et al., (1942) found that the upper lethal temperature of goldfish could be raised to 41°C by increasing the acclimation temperature to the limit, 36.5°C. Iezzi, et al., (1952) were able to acclimate the following fish species to higher lethal temperatures: Bluegill sunfish (*Lepomis macrochirus macrochirus*), brown trout (*Salmo fario*), bluntnose minnow (*Hyborhynchus notatus*), brown bullhead (*Ictalurus nebulosus*), and fathead minnow (*Pimephales promelas*). Black (1953) found that the black bullhead (*I. melas melas*) and carp (*Cyprinus carpio*) could be acclimated to higher temperatures. Cairns (1956) acclimated channel catfish (*I. punctatus*) to 86°F, enabling the fish to survive 95°F. Cocking (1959a, 1959b) studied the acclimation of roach (*Rutilus rutilus*).

Trembley (1960, 1961) found that the following fish could be acclimated to higher water temperatures: rock bass (*Ambloplites rupestris*), fallfish (*Semotilus corporalis*), white sucker (*Catostomus commersoni*), golden shiner (*Notemigonus crysoleucas*), common shiner (*Notropis cornutus*), spottail shiner (*Notropis hudsonius*), killifish (*Fundulus diaphanous*, *F. heteroclitus*), white catfish (*I. catus*), largemouth bass (*Micropterus salmoides*). Many of these fish could be acclimated to 75-80°F, in which condition they had an LD_{50} approaching 100°F.

Sumner and Douderoff (1938) compared the development of heat resistance in the gobies of *Gillichtys mirabilis* held at 30°C as compared with control fish at 20°C. For the controls, 37.73°C was lethal in 4.9 minutes. In the acclimating fish, resistance was conspicuous after only a half hour at 30°C, increased markedly by 9 hours (38.89°C; 34.4 minutes), then increased more slowly up to 10 days (39.62°C; 62.2 minutes). Of course, there is a ceiling to the acclimation temperature (see Figure III-

Different methods of acclimation have been tried. Fry, et al.,

(1946) acclimated young speckled trout (Salvelinus fontinalis) at a rate of 1°C rise per day, a method which they felt might serve for all types of fish. Cocking (1959b) said that a 1/20°C per hour rise (1.2°C per day) until the desired temperature was reached gave complete acclimation of roach, resulting in higher lethal temperatures than those achieved with faster methods of acclimation. Tyler (1966) also had good success with this method.

Before stocking rainbow trout in lower Nashotah Lake in southeastern Wisconsin, Threinen (1958) acclimated the fish in the following way. They were placed in a tank truck containing the same spring water in which the fish had been living. The temperature was the same 51°F. The truck was allowed to stand in the sun from 9:00 a.m. until 6:00 p.m. when the temperature had reached 63°. The next morning sufficient warm water was added to increase the temperature to 65°. The fish were then put into the tank which had a surface water temperature of 73°F. No mortality was observed. Many workers have observed that acclimated fish lost this acclimation slowly.

Acclimation of organisms occurs in their natural habitat with seasonal temperature changes. For example, Hathaway (1928) found that the gradual natural rise in stream water temperature in the spring raised the upper limit of temperature tolerance of five fish species inhabiting that stream. The species were yellow perch, largemouth bass, bluegill, pumpkinseed and toad tadpoles. Brett (1944) determined the upper lethal temperature of a number of fish species in Canadian lakes at 2-week intervals from the middle of May to the middle of September. The upper lethal temperature rose with increasing lake temperatures for the following species studied: bullhead, golden shiner, creek chub, fathead minnow, redbelly dace and finescale dace.

Trembley (1960) described an interesting case of natural acclimation which developed in a week. On May 7, he observed a school of alewives trapped in the lagoon. This lagoon had a temperature gradient from 80° to 90°F. All the fish were milling about in the 80° water. When his movements frightened the alewives into the hotter water, many died of heat shock. On May 14, the lagoon had warmed to a gradient of 83° - 92°F. Again the fish were swimming in the coolest water which now, however, was 83°, a temperature which had been lethal the previous week. This illustrates nicely the lethal effect of sudden changes in temperature as opposed to gradual changes. Hubbs (1964) observed increased resistance to thermal shock in the greenthroat darter with increased temperature fluctuations.

Information on the acclimation of animals other than fish is somewhat limited, but a few cases may be cited. For example, Dallinger (1897) reported the heat acclimation of several flagellated protozoans. Hathaway (1928) was able to acclimate amphibians. Segal (1956) observed heat acclimation in an intertidal mollusk. The marine copepod, Calamus finmarchicus, was able to acclimate to higher heat ranges (Halcrow, 1963). Sprague (1963) obtained heat acclimation in several crustaceans, Asellus, Hyalella, and Gammarus.

Rao (1967) has developed a most interesting diagram III-11 of the biological interrelationships occurring during cold acclimation. The common earthworm (Lampito maurith), the freshwater fish (Etropus maculatus), and the scorpions (Heterometrus fulvipes and H. swammerpatti) are examples

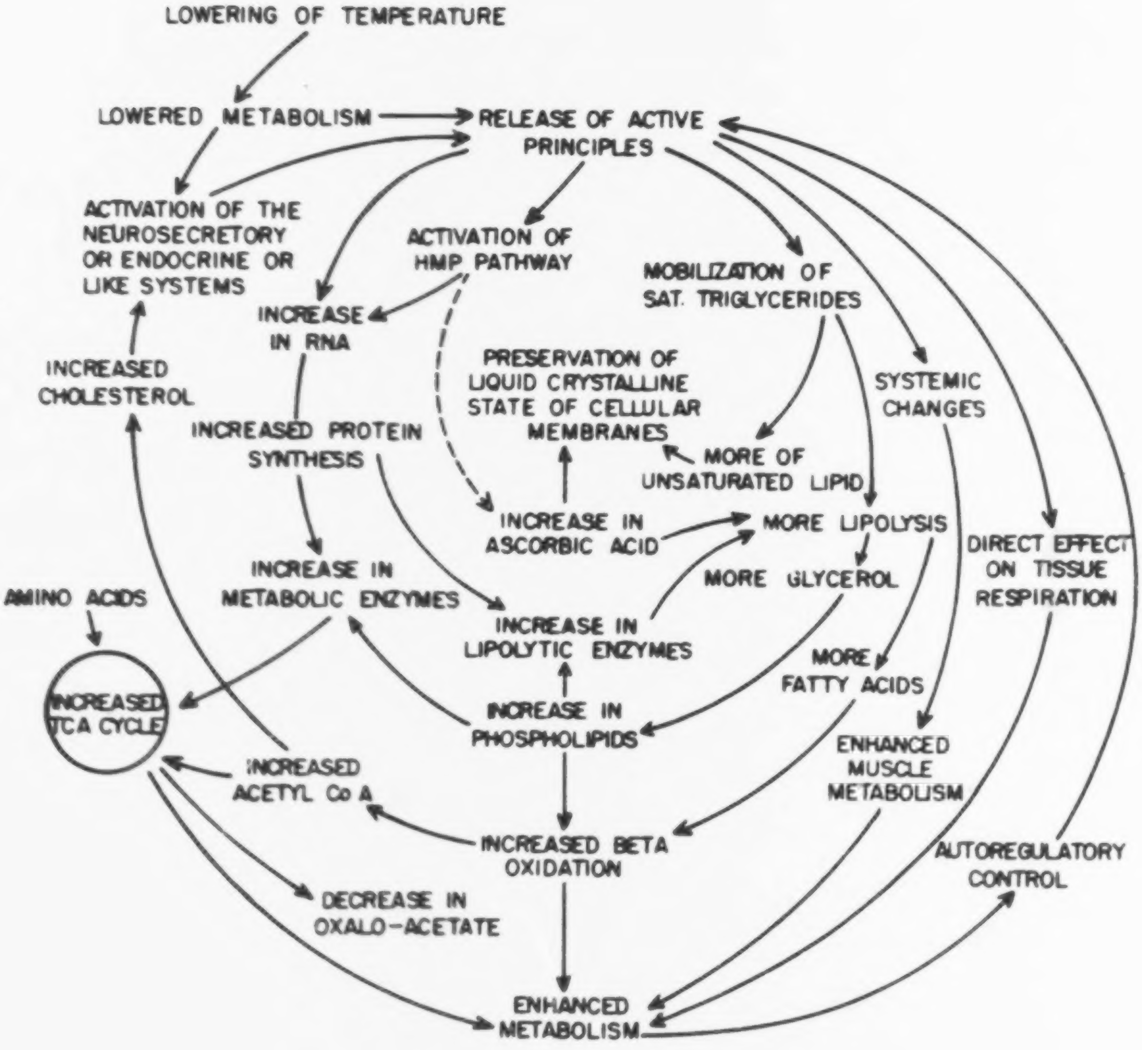

LOWERING OF TEMPERATURE
LOWERED METABOLISM
RELEASE OF ACTIVE PRINCIPLES
ACTIVATION OF THE NEUROSECRETORY OR ENDOCRINE OR LIKE SYSTEMS
ACTIVATION OF HMP PATHWAY
MOBILIZATION OF SAT. TRIGLYCERIDES
INCREASE IN RNA
INCREASED CHOLESTEROL
PRESERVATION OF LIQUID CRYSTALLINE STATE OF CELLULAR MEMBRANES
SYSTEMIC CHANGES
INCREASED PROTEIN SYNTHESIS
MORE OF UNSATURATED LIPID
INCREASE IN ASCORBIC ACID
MORE LIPOLYSIS
DIRECT EFFECT ON TISSUE RESPIRATION
INCREASE IN METABOLIC ENZYMES
MORE GLYCEROL
AMINO ACIDS
INCREASE IN LIPOLYTIC ENZYMES
INCREASED TCA CYCLE
MORE FATTY ACIDS
INCREASE IN PHOSPHOLIPIDS
ENHANCED MUSCLE METABOLISM
INCREASED ACETYL Co A
INCREASED BETA OXIDATION
AUTOREGULATORY CONTROL
DECREASE IN OXALO-ACETATE
ENHANCED METABOLISM

FIGURE III - 11 INTERRELATIONSHIPS OF BIOCHEMICAL CHANGES DURING COLD ACCLIMATION

of the poikilotherms utilized to determine biochemical changes during cold acclimation. Many of these changes were also found to occur in plants at the onset of winter. Interestingly enough, many of those changes were also noted in homeotherms during cold acclimation. All of the changes observed are reversible; and the reverse changes occurred during warm acclimation, although the triggering mechanisms occur in cells differing in position from those in the cold.

There is evidence that many aquatic plants, including bacteria, are able to respond protectively to harmful environmental conditions. For example, Brock (1967) observed the growth of blue-green algae at the very elevated temperatures (50-75°C) of hot springs in the Yellowstone National Park.

It is evident that this biological property of acclimation not only works naturally to protect aquatic flora and fauna, but also may be utilized purposefully in stream management by regulating initial effluent discharge so as to give the water organisms an opportunity to acclimate to increasing temperatures.

F. Temperature Selection

Observations of heated water discharges have indicated that fish tend to move toward them in colder months and to move away during summer months. This is an example of so-called temperature selection by motile organisms. In other words, they move toward some preferred temperature. Considered another way, this is also temperature avoidance, since the organism is migrating away from an undesirable temperature. This phenomenon of temperature selection then is a type of protective response. It is well established that most organisms when free to move in a gradient of temperature, tend to congregate in a definite narrow range of temperature (Fisher and Scott, 1942). Avoidance reactions (temperature selection) are common in nature, e.g., seasonal bird migrations.

Doudoroff (1938) reported that Girella nigricans and other marine fish showed marked selection of temperatures which were relatively high in comparison with their normal environment. Also, the fish tended to avoid areas subject to rapid changes in temperature. Silliman (1943) found that the vertical distribution of eggs and larvae of the pilchard (Sardinops caerulea) was correlated with the vertical temperature gradient of the water. The author suggested that this relationship could arise as a result of the larvae seeking an optimum temperature. Vertical distribution of the eggs reflect the vertical distribution of the parent fish at the time of the spawning, the parent fish presumably selecting water of the desired temperature (or specific gravity). Examples of species of fish showing temperature selection were largemouth bass (Fowler, 1940), young Pacific salmon (Brett, 1952), speckled trout (Sullivan and Fisher, 1953), carp (Pitt, et al., 1956), roach (Alabaster and Downing, 1958), rainbow trout (Garside and Tait, 1959, and Threinen, 1958), young sturgeon (Dzyan, 1962), and golden shiner (Trembley, 1960).

In a study of the depth distribution of fish in Norris Reservoir in Tennessee, Dendy (1945) found that, although some warm-water fish, such as shad, had a wide range of distribution with respect to water temperature, the distribution of the greater concentrations (middle 50 percent) of fish of most species was rather closely related to water temperatures. Most species tended to move to deeper water as the summer progressed and as the isotherms moved downward.

Dryer and Benson (1957) described operations at the New Johnsonville Steam Plant. Water for condenser cooling is drawn from Kentucky Lake and the spent water, raised in temperature ca. 10°F, is released into a rectangular discharge harbor from which it eventually flows back into the lake. Tremendous numbers of shad were observed in the discharge harbor during winter months, probably attracted by the warm water. The shad became rare in the harbor after March 15 when the temperature approached 60°, but about that time, blue catfish, channel catfish, and bluegill began to concentrate in the harbor. The catfish left the harbor in July when the temperature exceeded 80°.

In the case of certain species, higher temperature of acclimation resulted in the fish selecting a higher water temperature (Ferguson, 1958 and Badenhuizen, 1967), while with other species, the fish had the same preferred temperature, regardless of acclimation temperature (Brett, 1952 and Fry, 1958).

Mantleman (1960) found that very young fish reacted most quickly in avoiding undesirable temperatures. Badenhuizen (1967) studied the speed of selection by Tilapia and found that, after three minutes of exploratory behavior, the fish made their choice of temperature.

Trembley (1960) described an interesting episode of temperature selection in a natural habitat. Brown bullheads were observed in the cool section of the lagoon. The water in the lagoon had a temperature gradient of 89 to 106°F with the fish in the 89-90° zone. These fish would swim into the 104° zone to capture worms thrown into the water, but would immediately retreat to the preferred zone.

Alabaster (1963) described field observations which indicated that larger fish move away from heated effluents. He also described experiments placing fish in artificially-produced temperature gradients. The fish clearly avoided certain high temperatures; trout and bleak seldom swam into water warmer than 20°C, while grayling and tench never went into water warmer than 18 or 26°C, respectively. In experiments to determine what rate of temperature change caused fish to move from a certain location, Alabaster (1963) found that a rate of increase of 1°C per day over a period of eleven days induced no movement. Presumably, this rate of change was slow enough to allow acclimation. On the other hand, a sudden increase in river temperature of 6-9°C was sufficient to drive fish away.

The cited data on temperature selection (or avoidance) indicated that fish will not remain in a potentially harmful environment but instead will move toward a more favorable situation if an escape route is available and the more favorable situation is presented, as for example, cooler depths in a stratified lake or river. The general conclusion is that the majority of fish, given the opportunity, successfully avoid lethal temperatures.

Unfortunately, during some of the critical life stages, i.e., egg and fry development, the organisms are capable of little or no motility and, therefore, they are subjected to the environmental conditions within a small area.

Although little information is available on temperature selection by other aquatic vertebrates and invertebrates, it is reasonable to assume that all motile organisms possess some capacity to select desirable temperature conditions. For example, as Strickland (1969) said, "Probably the first thing is that a ribbon of hot water will appear..., zooplankton will look at it askance, depart the area and nothing bad will happen." Sessile organisms, of course, would lakc this protective response.

G. Thermal Pollution and Dissolved Oxygen Content of Water

A frequently expressed fear is that, as increased ambient heat speeds up the metabolic activities of fish and other aquatic animals, thereby increasing the oxygen requirements of the animals, the same elevated heat level reduces the amount of oxygen which a given volume of water can dissolve. In other words, increased demand occurs at a time of reduced supply.

H. Oxygen Requirements of Fish and Other Aquatic Animals

Agersborg (1930) reported that certain fish and small animals are nearly independent of the oxygen content over a wide range of dissolved oxygen (D.O.) concentrations while others adjust to the available oxygen supply. In summer trials on lake fish at 15-26°C, Moore (1942) showed that oxygen concentrations near 5 mg/l were well tolerated by all fish, but that concentrations below 3.5 mg/l were fatal to all species in less than 24 hours.

Ellis (1937) in a study of 982 stations on streams in the United States found that, in the warm seasons, the waters of those stations where a good, mixed fish fauna was observed, carried at least 5 mg/l of dissolved oxygen. However, Jones stated that the limiting concentration for most fish is below 3 mg/l (1964).

The British Ministry of Agriculture, Fisheries and Food (1961a, 1961b) investigated the behavior of fish in oxygen gradients. The research showed that the fish began to avoid low concentrations of oxygen long before the lethal concentrations were reached. The fish returned when the concentration of D.O. became higher.

Burdick, et al., (1954) found that for brook trout at 55°F the mean lethal concentration of oxygen was 1.59 mg/l, while at 70° it was 2.54 mg/l. For brown trout, the mean lethal concentration was 1.42 mg/l at 49° and 2.53 mg/l at 69°. For rainbow trout, the mean lethal concentration was 1.05 mg/l at 52° and 1.82 mg/l at 71°. For smallmouth bass, the data were 0.63 mg/l at 52.5° and 1.15 mg/l at 80°.

One symptom of respiratory distress in fish is an increased tendency to swim. This may be because the fish senses the unfavorable nature of the environment and tries to find more highly aerated water, but it is partly due to the fact that forward movement assists the flow of water through the mouth and gill chambers (Jones, 1964). In his experiments, Jones observed that fish would enter water very deficient in oxygen and extreme respiratory distress would develop, but the fish would always continue to swim. When this random movement carried them into well-aerated water, they recovered very rapidly.

In regard to D.O. relationships in invertebrates, Sprague (1963) reported high resistance to oxygen deficiency in several aquatic crustaceans. He found concentrations of oxygen causing 50 percent kill in

24 hours were 0.03 mg/l for Asellus intermedius, 0.7 mg/l for Hyalella azteca, 2.2 mg/l for Gammarus pseudolimnaeus and 4.3 mg/l for G. Fasciatus. The oxygen values were for animals acclimated and tested at 20°C. This resistance fit field observations very closely.

I. Natural Fluctuations in the Dissolved Oxygen of Water

It is obvious that an aquatic community survives seasonal fluctuations in the D.O. content of the ambient water. Dorris, et al., (1963) found that the D.O. concentration of the middle Mississippi River ranged from a low of 4.4 mg/l in mid-July to a high of 14.2 mg/l in early April. Reduction of D.O. with depth in a stratified lake or impoundment is well documented. The D.O. of the hypolimnion may even reach 0.0 mg/l. The aerobic biota of the waters survive these conditions, usually by moving out of the zone of oxygen depletion. The benthic community, containing organisms which are sessile or capable only of slow movement, might suffer damage. However, most bottom organisms are adapted to anaerobic metabolism.

J. Dissolved Oxygen Changes Caused by Discharge of Heated Effluents - Changes During Passage Through the Condensers

In the period 1955-57, Markowski (1959) studied the environmental effects of discharged cooling water from twelve power stations in England and Wales. He reported on spot checks of the D.O. in the influent and effluent cooling water. His results are summarized in Table III-3. The oxygen content of the water discharged from the condensers is changed very little from that of the influent and is even increased in some cases.

TABLE III-3

Effect of Condenser Passage Upon Dissolved Oxygen of Cooling Water

(from Markowski, 1959)

Power Station	Date of Survey	Inlet Water			Outlet Water		
		Temp. °F	°C	D.O. mg/l	°F	°C	D.O. mg/l
Leicester (open)	June 26, 1956	73	22.8	6.2	88.3	31.3	6.6
Leicester (closed)	Aug. 29, 1957	72	22.2	8.4	84.6	29.2	8.1
Wakefield "B"	June 27, 1956	68	20.0	4.4	76.2	24.6	5.6
Wakefield "B"	Sept.25, 1956	63.5	17.5	6.2	77	25.0	7.1
Wakefield "B"	Aug. 20, 1957	65	18.3	2.9	78	25.5	4.8
Carmarthen Bay	July 31, 1956	61.9	16.6	7.8	72	22.2	7.9
East Yelland	Aug. 9, 1956	65	18.3	9.8	75	23.9	8.3
Plymouth	Aug. 21, 1956	67	19.4	7.0	62.5	16.9	7.3
Poole	May 15, 1956	58	14.4	8.1	75	23.9	8.2
Poole	Sept. 3, 1956	59	15.0	7.9	75	23.9	7.9
Roosecote	Sept.11, 1956	62.5	16.9	8.5	73.8	23.2	8.2

Trembley (1960) in his classic study at the Martins Creek Steam Electric Station on the Delaware River near Easton, Pennsylvania, made D.O. measurements on the river at the cooling water intake and at several points along the discharge canal. Some of his data are given in Table III-4. At this plant, passage through the condensers almost invariably reduced the D.O. of the cooling water, but seldom to a critical level. The lowest D.O. recorded at the discharge structure was 3.4 mg/1, this occurring during August. This would hardly constitute a hazard to aquatic life, considering the eventual dilution with higher D.O. water upon return to the river.

During the summer of 1960, the Subcommittee on Water Utilization of the Pennsylvania Electric Association carried out water temperature surveys on streams in the vicinity of 22 steam electric stations (Mason, 1962). The stations were chosen to provide geographical distribution and to include most of the important streams in the Commonwealth of Pennsylvania. D.O. measurements were made at some of these stations, including input and output cooling water. At Warren Station on the Allegheny River, there was a drop of only 0.6-0.8 mg/1 D.O. in the cooling water passing through the plant, while at the Seward Station there was practically no oxygen depletion. At New Castle Station on the Beaver River, there was no reduction between plant intake and plant outflow at any time of the day.

K. Changes in River and Lake Water Below Heated Discharge Outfall

The Subcommittee on Water Utilization of the Pennsylvania Electric Association (Mason, 1962) studied the oxygen content at 32 points

TABLE III-4

Effect of Condenser Passage Upon Dissolved Oxygen of Cooling Water (from Trembley, 1960)

Date	Normal River*		Discharge Canal at Discharge Structure		Discharge Canal at River	
	Temp. °F	D.O. mg/1	Temp. °F	D.O. mg/1	Temp. °F	D.O. mg/1
1956:						
April 2	40	10.0	72	6.5		
June 11	68	7.7	92	3.4	92	4.6
July 10	70	6.5	94	5.0	94	5.5
Aug. 1	74	5.4	104	3.6	103	3.8
Sept. 7	64	5.0	89	4.3	80	4.3
Oct. 2	58	6.3	82	6.3	82	5.9
Oct. 23	58	6.8	81	5.8	81	6.8
1957:						
June 22	79	7.1	105	5.7	104	7.1
July 27	76	6.7	101	5.8	100	6.0
Aug. 23	74	9.2	99	6.9	98	7.1
1958:						
June 8	78	10.2	103	7.0	103	6.0
July 2	83	8.8	110	6.4		
Sept. 9	80	7.7	106	7.2		
Sept. 22	64	8.8	91	7.8		

*River at or near intake

along the moderately-polluted Schuylkill River on which are located several power plants. The river temperatures at these points ranged from 82° to 99°F. The D.O. varied from 5.0 to 15.3 mg/l. The field data obtained by the Subcommittee permitted the conclusion that "no power station is so altering the dissolved oxygen content of its receiving stream that it is causing a deleterious biological effect from this factor." (Mason, 1962)

Appourchaux (1965) in a 2-year study found that the discharge of condenser water from the Montereau Central Power Station into the Seine River did not alter the concentration of the river D.O.

Slack and Clarke (1965) reported that when the temperature of the West Branch of the Susquehanna River below the Shawville Steam Electric Power Plant was highest, the D.O. was reduced but did not fall below 7.0 mg/l.

Gammon (1968) found at the Belvedere Power Station that there was significant aeration of the heated cooling water in the outfall system. This resulted partly from aeration in the exit tunnel, but largely from aeration during the water drop at the siphon seal weir when the receiving water level was lower than the weir. At low water nearly 2 mg/l D.O. were added to the cooling water by this fall at this weir.

In a study of the power plant of the Kansas City Power and Light Company on Montrose Lake, Campbell, et al., (1966) found that the D.O. of water in the lake just beyond the outfall from the power plant (Station 4) was usually higher than the D.O. at the plant intake (Station 10). No description of the cooling water discharge system was given.

Beer and Pipes (1968) in a study of the effects of thermal pollution on Lake Michigan, reported that the D.O. remained essentially unchanged at 11.0-11.5 mg/l within the area of influence of the heated discharge.

In the light of the evidence, the fears expressed concerning lethal reductions in the D.O. of streams and lakes caused by heated effluents seem quite unwarranted.

L. Natural Fluctuations in Temperature

Since any body of water undergoes temperature variation without apparent elimination of the normal flora and fauna, it would appear that normal fluctuations in water temperature are not harmful to the aquatic community. However, the very structure of the community and the geographical distribution of an aquatic species could well be greatly dependent on diurnal and/or seasonal temperature extremes.

Furthermore, the lethal temperature limits are effected by fluctuating temperature. Studies by Whitney (1939) and Hubbs (1964) indicate increased resistance to thermal shock in animals subjected to wide natural temperature variations. Brett (1956) referred to this phenomenon as summation of acclimatization.

Surface water temperatures in the Mississippi River near Quincy, Illinois, ranged from 0°C in late January to 33.2°C in July (Dorris, et al., 1963). The yearly temperature curve based on weekly measurements showed numerous dips and rises with differentials up to 5°C.

Burnson (1938) observed that the temperature of the top water in the San Pablo Reservoir was 50°F in January and 68°F in July, while the bottom water ranged from 50°F in January to 63°F in August. In the San Leandro Reservoir, the top water range was 50-74°F while the bottom water range was 50-62°F.

DeRoche and Bond (1955) found lake trout and twenty other species of fish in Cold Stream Pond at Enfield, Maine, which had a vertical temperature distribution from 50° to 70°F. The temperature variation in the Guadalupe River in Texas ranged from 7°C to 35°C (Hubbs, 1957).

Moore (1958) presented a figure based on ORSANCO data for Raccoon Creek, a tributary of the Ohio River. This stream, which received no thermal load, showed a variation from 35° to 75°F during the year. Whitney (1939) reported that it is by no means uncommon to measure a difference of 3°C between the middle of a stream and fairly stagnant water at the shore.

M. Artificial Fluctuations in Temperature

Modern electrical generating systems usually operate with hydro power in conjunction with steam generated power (Krenkel and Parker, 1969). During periods of high flow the steam plants demonstrate wide fluctuations in load and thus rejected heat, while the hydroplants operate as base load plants if sufficient water is available. Otherwise, hydroplants do take the peaks, but steam plants must also fill in some of the peaking needs. Conversely, during periods of low flow, the steam plants operate on base load and the hydroplants show wide variation in flow and temperature.

Typical curves of river temperature below a steam plant demonstrating diurnal variation as much as 14.4°F have been presented by Gameson, et al. (1959). Alabaster (1962) points out that temperature maxima may be attained within a few hours, and although the maxima may not reach ultimate lethal levels, the rapid attainment of these maxima may kill fish.

Also, the temperature change below a peaking power hydroelectric plant during periods of low flow may be as much as 18°F within a few hours with a corresponding flow rate change of 8000 cfs according to Krenkel, et al. (1965). The Tennessee Stream Pollution Control Board has reported several fish kills caused by this rapid change of temperature (Jones, 1966). Brett (1960) states that rapidly onsetting low temperatures can constitute one of the greatest threats to survival when fish are accustomed to relatively warm water because of the inherent slow rate of acclimatization to low temperatures.

N. Effect of Elevated Temperature Upon Biological Populations of Rivers

Workers in this area are interested in the effects of heat upon (a) entrained organisms, i. e., those relatively small plants and animals that are present in the cooling water pumped through the condensers, and (b) organisms in the open water, i. e., animals and plants in the river or lake serving as receiving water for the heated discharge.

O. Effect Upon Entrained Organisms

On September 25, 1965, Markowski (1959) made a quantitative study of the zooplankton in the intake and outfall waters of a power station which used freshwater for cooling. The temperature rise varied from 17.5° to 24.4°C. He collected five samples at each location. A sample consisted of 50 l. of water filtered through a 180-mesh (74/cm) plankton net. All of the animal phyla found in the intake waters were likewise observed in the effluent water and in most cases in greater numbers of individuals. Only living organisms were counted. The condenser water was chlorinated and the effluent still had a chlorine residual of 0.2 mg/l.

Markowski concluded that passage of cooling water through power station condensers had no harmful effect upon the organisms in the cooling water since the organisms exposed to chlorination, turbulence, and heat were not only alive but able to reproduce. Of course, condenser passage time and hence exposure time is very short.

Conversley, Mihursky and Cronin (1967) concluded that in an estuarine environment, if the pumping volumes at a steam-electric station are a significant percentage of the total available water supply, extensive population sags of entrained organisms can be expected. Using sea nettles as an indicator, they showed a significant decrease in entrained organisms below a Maryland steam-electric station after startup as compared to an earlier period.

P. Effect Upon Periphyton

Trembley (1960) chose the periphyton as a group of organisms showing promise as an indicator of the effects of heated discharges. Periphyton is a collective name for all those aquatic plants and animals which attach to solid surfaces exposed to natural waters. It thus overlaps both the benthic and the planktonic populations, but does not include all the members of either.

To follow changes in periphyton population of the river, Trembley used a so-called pralgometer, which is simply a device for suspending microscope slides in the stream a few inches under the surface. Only one point in each river transect was sampled. Stream organisms attach to the glass slides, even grow, within a few days. Differences in counts (species and individuals) above and below the source of heated water should indicate the effect of the heat upon the periphyton population.

Trembley concluded that the periphyton was considerably altered by the power plant discharge. Return to normal conditions occurred by 4,500 feet downstream. At Widows Creek (TVA, 1967) the autotrophic index indicated no interference with normal periphyton productivity by the waste heat.

Q. Effect on the Benthos

In a river, most of the microscopic population are benthic organisms, since plankton have difficulty maintaining position in the stream flow. The benthos is a stationary community which should reflect the action of the temperature in the area of influence. Of course, bottom debris may serve to protect benthic organisms to some extent from full exposure to the heated water.

Trembley (1960) studied the bottom fauna of the Delaware River at the Martins Creek Power Plant. Samples were taken at 2-week intervals at riffle areas with the Surber stream bottom sampler. In the zone of maximum temperature rise just below the outfall, there was obvious reduction of species and individuals. In the cool water unaffected by the thermal overflow, there was no reduction in macroinvertebrates. During the cooler seasons of the year, there was repopulation of the areas affected during the hot months by the thermal discharge. Even during the summer, there was a significantly higher standing crop at the downstream Little Kaypush site in comparison to the normal river control station.

Coutant (1962) followed Trembley's Martins Creek research with a study of the macro-invertebrate bottom fauna of the riffle areas of Big Kaypush and Little Kaypush Rapids. He confirmed Trembley's conclusions. From July through October, there was substantial reduction in the number, diversity and biomass of benthic organisms in that portion of Big Kaypush Rapids lying in the path of the heated water. At a distance of one mile downstream from the point of discharge, he found an essentially normal population structure. In his traverse studies, Coutant observed an increase in both variety and number of organisms as he progressed from hot to cool water, demonstrating the effect of temperature as the primary limiting factor. The work also showed the restricted effect of heated discharges in changing the biological communities. The data suggest a tolerance limit near 90°F for a normal population structure with extensive loss in numbers and diversity of organisms accompanying further rise.

Wurtz and Dolan (1960) reported a study on bottom organisms in the Schuylkill River at the Cromby Power Plant. These authors gave no temperature data; however, the Subcommittee of the Pennsylvania Electric Association (Mason, 1962) showed severe temperature alteration in this reach of the river since the plant used some 85% of the river flow as cooling water leaving little cool water for dilution. The river showed a very elevated temperature and slow recovery. Wurtz and Dolan evaluated the effects of heated discharges in terms of biological depression, biological distortion, and biological skewness. Station 10 at the Phoenixville Pumping Station, 0.5 mile below the power plant, showed the greatest deviation from normal conditions. At Station 13, six miles below the power plant, the river biology had recovered from the effects of the waste heat. No intermediate stations were sampled. This case illustrates ultimate recovery from an extreme condition.

Mann (1965) studied the bottom fauna at points above and below the Earley Power Station. The species composition of the benthos showed little difference. The main feature was a change in the abundance of various members of the community. He found no evidence that benthic animals had been killed by the heated effluent. In the light of his temperature profiles, Mann's failure to specify exactly where across the transect of the river the samples were collected makes it difficult to accept his evaluation of the data.

It is clear from the valid biological data presented above that increased temperature of the water does alter the species and individual composition of the benthic population which, of course, being generally sessile, is unable to avoid exposure.

R. Effect on Aquatic Plants

Once each year during the 4 years of his research, Trembley (1960) made a detailed survey of the rooted aquatic vegetation and algae on both sides of the river above and below the Martins Creek plant. There appeared to be little difference in growth at these upstream and downstream points. In 1958 and 1959, specimens of *Elodea* and *Potomogeton* were found growing directly in the path of the warm water, indicating acclimation of these plants.

Abundant growths of blue-green algae occurred in the discharge canal and in the river on the Pennsylvania side for 1500 feet below the discharge canal, green algae were abundant in the river during the summer. Some green algae were growing in pools in 100°F just below the discharge canal.

5. Effect on Fishes

Trembley (1960) made observations on fish distribution at the Martins Creek Plant site from 1956 through 1960. Specimens were taken by seining, fyke netting, trap netting, trot lines, angling, electrofishing and rotenoning. He arrived at the following conclusions:

1. All the fish species normally inhabiting the unheated Delaware River at the plant location, with the exception of shad, may be found living in the heated water section at one time of the year or another.

2. During the warm months, there is almost complete elimination of most species from the zone of maximum heat. This is probably avoidance rather than killing.

3. During the cold months, there is a congregation and extended period of feeding activity of many species in the heated zones of the river.

4. Repopulation of the zone of maximum heat occurs, chiefly due to an influx of fish from waters of normal or near normal temperatures surrounding the affected zone.

5. There was evidence of successful migration of four anadromous species of fish through the power plant area under the existing conditions of temperature distribution.

6. The only fish kills occurred among trapped fish exposed to a sudden sharp rise in temperature.

Alabaster (1963) attempted to determine the effect of heated effluents upon fish populations counted by trapping. At Earley, Goldington and Little Barford stations, there was no significant difference between catches above and below the outfall. These are peak load stations and the river was stratified. At Leicester and Staythorpe, more fish were caught in the warm water than in the normal river. At Castle Donington, the fish gathered in warm water in 1958, but avoided the warm water in 1959. At these stations, the discharges were 6.3-10.4°C hotter than normal river temperature.

T. Effect of Elevated Temperature Upon Biological Populations of Lakes

In 1949, a dam was built on Morgan Creek, a small tributary of the Upper Colorado River in north-central Texas to form a reservoir (Lake Colorado City) which was to serve as a supply of cooling water for the steam-electric power plant constructed soon afterward on the shore of the lake (Campbell, 1960). The capacity of the reservoir at service spillway level is 31,800 acre-feet. The reservoir is about 3 1/2 miles long and 2 miles wide.

The upper half of the lake was heavily utilized for recreational purposes, but public access to the lower half of the reservoir was restricted by the power company. Water for cooling was withdrawn from the lake at an intake on the north shore of the restricted area and the heated effluent discharged back into the restricted area by way of discharge canals. The return water flowed over a weir, falling freely into the reservoir. The circulating flow created in this manner was 320-600 cfs. The maximum temperature of the discharge was 36°C (96.8°F). The overall effect on the lake was to reduce extreme temperatures during the winter and to increase extreme temperatures in summer.

Campbell (1960) studied the fish population of Lake Colorado City and found production to be excellent. The game fish-rough fish ratios were more favorable than for most of the area reservoirs. The carpsucker and the carp constituted a threat to future production of game species , however.

There appeared to be an attraction to and a concentration of fish in the restricted area around the power plant during the summer months. This was true for gizzard shad, channel catfish, carp and white bass. Channel catfish, shad and river carpsucker were observed milling in and about the race created by the ten-foot fall of water over the weir at the end of the discharge canal. Great difficulty was experienced trying to keep poachers out of this area. During the winter months, there was a notable increase in largemouth bass and white crappie. While the recreational area of Lake Colorado City has an excellent reputation for fishing, the restricted (heated) region of the lake is regarded as a sort of Utopia by sportsmen.

Beer and Pipes (1968) studied the effect of condenser water discharge on the nearshore environment of Lake Michigan. The observations were made near the outfall of a generating station located 40 miles north of Chicago. The study period was April, 1968. Normal lake temperature averaged 48°F. The cooling water requirement was 760,000gpm. The effluent was discharged into the lake by way of a 2,000-foot plume at a temperature of 60°F. and a velocity of 2.61 ft/sec. The lake bottom sloped to a depth of 32 feet at 3,000 feet offshore.

Because of the limited number of samples collected in the study, it was not possible to draw definite conclusions about environmental effects. However, the discharge of cooling water at Waukegan had not completely eliminated any of the benthic organisms important in the food chain of commercial and sport fish.

The New Johnsonville Steam Power Plant, located on Kentucky Lake, discharges cooling water into a harbor which empties into the lake. Dryer and Benson (1957) found harbor temperatures 10°F. higher than lake temperatures from October, 1955 to April, 1956. In April and May, harbor temperatures were only 5°F. to 6°F. above lake temperatures.

Tremendous numbers of threadfin shad and an abundance of plankton were found within the harbor during the winter months. Large numbers of skipjack and sauger appeared in the harbor during the same period, apparently to feed on the shad.

The presence of large numbers of catfish during April, May and June was believed to result from excellent spawning habitat in the dikes' riprap rather than from the elevated temperatures.

U. National Technical Advisory Committee on Water Quality Criteria Recommendations

In 1968, the National Technical Advisory Committee on Water Quality Criteria submitted to the Secretary of the Interior "The most comprehensive document on water quality requirements to date." (National Technical Advisory Committee, 1968) The summary of the recommended temperature requirements for aquatic life were:

Recommendation for Warm Waters: To maintain a well-rounded population of warm-water fishes, the following restrictions on temperature extremes and temperature increases are recommended:

(1) During any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water (at the expected minimum daily flow for that month) more than 5°F. In lakes and reservoirs, the temperatures of the epilimnion, in those areas where important organisms are most likely to be adversely affected, should not be raised more than 3°F above that which existed before the addition of heat of artificial origin. The increase should be based on the monthly average of the maximum daily temperature. Unless a special study shows that a discharge of a heated effluent into the hypolimnion or pumping water from the hypolimnion (for discharging back into the same water body) will be desirable, such practice is not recommended.

(2) The normal daily and seasonal temperature variations that were present before the addition of heat, due to other than natural causes, should be maintained.

(3) The recommended maximum temperatures that are not to be exceeded for various species of warm-water fish are given in Table III-5.

Recommendation for Cold Waters: Because of the large number of trout and salmon waters which have been destroyed, or made marginal or nonproductive, the remaining trout and salmon waters must be

TABLE III-5

[Provisional maximum temperatures recommended as compatible with the well-being of various species of fish and their associated biota]

93°F: Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.

90°F: Growth of largemouth bass, drum, bluegill, and crappie.

84°F: Growth of pike, perch, walleye, smallmouth bass, and sauger.

80°F: Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.

75°F: Spawning and egg development of largemouth bass, white, yellow, and spotted bass.

68°F: Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.

55°F: Spawning and egg development of salmon and trout (other than lake trout).

48°F: Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

protected if this resource is to be preserved:

(1) Inland trout streams, headwaters of salmon streams, trout and salmon lakes and reservoirs, and the hypolimnion of lakes and reservoirs containing salmonids should not be warmed. No heated effluents should be discharged in the vicinity of spawning areas.

For other types and reaches of cold-water streams, reservoirs, and lakes, the following restrictions are recommended.

(2) During any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water more than 5°F (based on the minimum expected flow for that month). In lakes and reservoirs, the temperature of the epilimnion should not be raised more than 3°F by the addition of heat of artificial origin.

(3) The normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes should be maintained.

(4) The recommended maximum temperatures that are not to be exceeded for various species of cold water fish are given in Table III-5.

NOTE - For streams, total added heat (in BTU's) might be specified as an allowable increase in temperature of the minimum daily flow expected for the month or period in question. This would allow addition of a constant amount of heat throughout the period. Approached in this way for all periods of the year, seasonal variation would be maintained. For lakes the situation is more complex and cannot be specified in simple terms.

V. State Temperature Standards

Since that report was published, all fifty states, and five other jurisdictions have proposed maximum temperature and temperature rise criteria for interstate waters. Those proposed criteria are tabulated in Table III-6.

In all those temperature standards, the major concern appears to be with adult fish life. As more information is gathered concerning other aquatic species, and as the temperature requirements for the critical stages in the life history of all fish species are better defined, those standards can become more specific.

The evolution of more specific standards can be illustrated through the recent recommendation of new maximum temperature limits to the ORSANCO Engineering Committee. Using recently obtained information regarding temperature requirements for the critical life stages of important Ohio River fishes, Hokanson (1969a) presented what he considered a more meaningful maximum temperature standard than the earlier ORSANCO standards. The comparison of the average Ohio River temperature, the existing standard and the recommended standard appears in Figure III-12.

The Federal Water Pollution Control Administration, working primarily through its National Water Quality Laboratory is currently engaged in research which will establish the temperature requirements for the critical stages of selected fish species and important food web organisms. With standards which will protect those key organisms, it is believed that a diversified sport and commercial fishery superior in many places to those now existing can be realized (Mount, 1969).

TABLE III-6

LIMITING TEMPERATURE CRITERIA IN WATER QUALITY STANDARDS FOR INTERSTATE WATERS 1/

States and other Jurisdictions	Limiting Uses 2/														All Waters		Exceptions & Remarks
	Cold Water Fish		Small-mouth Bass		Warm Water Fish		Fish & Shell-fish		Recreation		Water Supply		Industrial				
	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	
Ala.															90	10%	Temp. may reach 93° for 8 hrs. per day. Not approved for shellfish or fish and wildlife uses.
Alas.					60	5%	68				60		70				Salt water.
					60	10%					60		70				Fresh water; 0.5% allowed if nat. temp. greater than 60°.
Ariz.	55				93	5											November-March
	70	2			93	5											April-October
Ark.	68	5	86	5	95	5											
Cal.																	Not approved. Allowable temperatures vary with stream and location.
Colo.	70				90								93				
Conn.												0			85	4	
Del.															75	5	Ocean
																5	Most streams.
															85-87	5	Some streams.
D.C.															90	5	
Fla.																	Shall not interfere with beneficial uses assigned to waters. Numerical criteria will be assigned following 1-year study.
Ga.		0					93	10	93	10	93	10	93	10			
Haw.																1.5	
Ida.															68	2	Except Snake-R.M.407-247, Max. 70°, rise 2°.
Ill.					60	5							90	5			December-March.
					90	5							90	5			April-November; open waters have max. temp. of 85° and 5° rise.
Ind.	65	9			93	9							95	9			April-Nov. Dec.-March-Above 65° allowed for coldwater fish if oxygen content greater than specified; 85° max. for Lake Michigan
Iowa															89	5	Miss. River-From Minn. to Wisc.-Ill. border.
															90	5	From Wisc.-Ill. border to Mo. border.
															90	5	Mo.River -May-Oct.
																10	-Nov.-April
															93	10	Other streams-not approved.
Kan.															90		Not approved.
Ky.															93	10	Mar.-Nov.(not approved)
															73	10	Dec.-Feb.
La.															97	5	Except some rivers with 95°max. and 4° rise.
Me.	68	4			83	4							90				Temp. standards not approved.
Md.	72				60	20											Nat. temp. less than 50°.
	72				93	10											Nat. temp. more than 50°; 90° max. for tidal.
Mass.																0	Class A.
	68	4		4	83	4		4		4		4	90				Others.
Mich.	70	10			85	10			90			10		10			Aquatic life temps. not approved. 15° rise allowed for warm water fish if original temp. is below 36°.
Minn.		0		0		0				0			75				Class 2A & 3A; 2 refers to Fisheries & Recreation
					86				86				86			5	Class 2B & 3B; 3 refers to industrial uses.
					90				90				90				Class 2C & 3C.
Miss.															93	10	10° rise not approved.

TABLE III-6

LIMITING TEMPERATURE CRITERIA IN WATER QUALITY STANDARDS FOR INTERSTATE WATERS 1/
(Continued)

States and other Juris-dictions	Cold Water Fish Max. Temp.	Cold Water Fish Max. Rise	Small-mouth Bass Max. Temp.	Small-mouth Bass Max. Rise	Warm Water Fish Max. Temp.	Warm Water Fish Max. Rise	Fish & Shell-fish Max. Temp.	Fish & Shell-fish Max. Rise	Recreation Max. Temp.	Recreation Max. Rise	Water Supply Max. Temp.	Water Supply Max. Rise	Industrial Max. Temp.	Industrial Max. Rise	All Waters Max. Temp.	All Waters Max. Rise	Exceptions & Remarks
Mo.															90	5	Except Des Moines where max.temp. is 93° and except No. Fork White, Current, and Eleven Point Rivers where max. rise is 2°.
Mont.	69	2			89	4								0			If orig.temp. is above 67° and 85°, 0.5° rise for fisheries.
Neb.	65	5			90	5				5		5					May-October.
	65	5				10				10		10					Nov.-April; except for Mo. River from Gavins P. to Sioux City which is 85° max. and 4° rise for warmwater fish.
Nev.	68				86												Summer. Some waters have summer max. 64°-81°, other waters have summer max. avg. daily temps. of 55°-77°.
															57		Winter.
N. H.													90				Criteria for fish not approved.
N. J.																0	FW-1 (preserve natural conditions).
	70	5			87	5											5° refers to avg.temp. grad. occurring in 1961-1966.
N. M.	70	2			93	5											10° rise allowed for lower reach of Pecos, which is not approved.
N. Y.		0			86	5											90° max. in mixing zone; 5° refers to permanent change.
								4									Sept. - May
								1.5									June - Aug.
N. C.	70				95		95						95			7	95° max.not approved, 7° rise refers to fresh warm water fisheries only.
N. D.															90		90° max. & 10° rise for Red River of the North - not approved.
Ohio	70				93												April-Nov. (Class A) Not approved
	70				60												Dec.-Mar. (Class A) Not approved
	70				95												Apr.-Nov. (Class B) Not approved
	70				73												Dec.-Mar. (Class B) Not approved
Okla.	70	5	75	5	93	5											
Oreg.															64	2	Generally.
															70	2	Multnomah Channel, Willamette, Snake.
															68	2	Columbia, Grande Ronde, Walla Walla.
															72	2	Klamath River
																0	Marine water.
Pa.	58	5			87	5											86° max. Delaware Estuary, 93° max. in Mahoning.
R. I.																0	Class A (preserve natural conditions).
	68	4			83	4							90			4	Class B & C.
S. C.															93	10	Fresh waters; 10° rise not approved; 93° max. approved only for Savannah, Tugaloo & Chatuge Rivers.
																4	Salt waters, winter.
																1.5	Salt waters, summer.
S. D.	68	4	75-85	4	90	8											
Tenn.															93	10	Not approved for fish and wildlife uses.
Tex.															96	5	Except Canadian & tidal waters.
															93	5	Canadian River.
																4	Fall, winter, spring-tidal waters.
																1.5	Summer-tidal waters.
Utah	68	2			80	4											

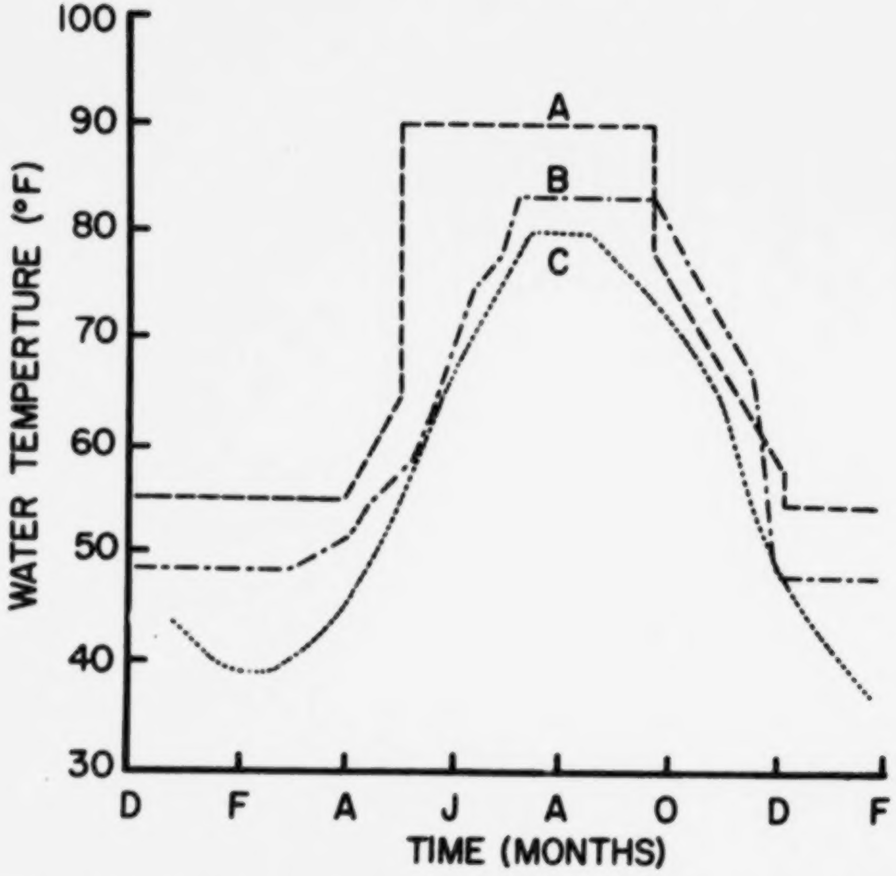
TABLE III-6

LIMITING TEMPERATURE CRITERIA IN WATER QUALITY STANDARDS FOR INTERSTATE WATERS 1/
(Continued)

States and other Juris-dic-tions	Limiting Uses 2/														All Waters		Exceptions & Remarks
	Cold Water Fish		Small-mouth Bass		Warm Water Fish		Fish & Shell fish		Recreation		Water Supply		Industrial				
	Max. Temp.	Max Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	Max. Temp.	Max. Rise	
Vt.	68				83	4							90				68° not approved; no increase for Class A waters
Va.					95												Not approved.
	70																Temp. rise criteria to be added within 1 yr. No thermal barriers to fish passage. No change for essential spawning areas.
Wash.															60	75/T-22	Fresh,ClassAA;T=Resulting
															55	24/T-39	Marine,Class AA water
															65	90/T-19	Fresh, Class A temp.
															61	40/T-35	Marine, Class A
															70	110/T-15	Fresh, Class B
															66	52/T-32	Marine, Class B
															75	125/T-12	Fresh, Class C
W. Va.															93	5	May-Nov.
															73	5	Dec.-Apr.;specific temps. are set for most streams.
Wisc.					89	5							89				84° max. where maintenance of fish reproduction is of primary importance.
Wyo.		2															Where nat. temp. less than 70°.
		4															Where nat. temp. greater than 70°.
Guam								1.5	85		85	5					
P. R.																0	Class A.
															93	4	Other waters.
V. I.																0	Class A.
															90	4	Fall, winter, spring; 1.5° rise in summer.

1/ The water quality standards proposed by all states and other jurisdictions have been approved by the Secretary of the Interior, although some approvals were with reservations including reservations relating to temperature criteria. The temperature criteria shown have been approved by the Secretary except as noted.

2/ Temperature criteria for most states include general restrictions which limit the effects of increase to that conducive to the limiting use of the water body. Classes are designated by the individual state involved and are not necessarily comparable with other states.



A MAXIMUM DAILY AVERAGE TEMPERATURES ALLOWED BY ORSANCO CRITERIA
B RECOMMENDED MAXIMUM DAILY MEAN TEMPERATURES
C FIVE YEAR (1963-1968) GRAND AVERAGE OF MAXIMUM AND MINIMUM DAILY AVERAGES FOR EACH MONTH AT CINCINNATI

FIGURE III - 12 COMPARISON OF ORSANCO WATER STANDARDS WITH OHIO RIVER WATER AND RECOMMENDED TEMPERATURES

In summary, it is appropriate to quote from the 1966 Symposium on Water Quality Criteria to Protect Aquatic Life where biothermal experts Mihursky and Kennedy (1967) stated that:

"Lessons from past environmental changes indicate environmental repair is difficult to economically or politically justify once the damage has occurred. The task concerning temperature considerations is to indicate exactly the ecological alterations to be expected under temperature regimes and to exactly determine the temperature requirements of the species involved. Undoubtedly, at the present level of understanding in this complex problem, it is imperative that a conservative point of view be maintained when establishing regulations."

W. Research Needs

Examination of the literature demonstrates that a most succinct summary of research needs in establishing the effects of temperature changes on aquatic life was promulgated by the National Technical Advisory Committee for Fish, Other Aquatic Life and Wildlife in its "Summary of Research Needed for the Determination of Water Quality Requirements for Aquatic Life and Wildlife", as quoted by Allen (1969).

The Committee, treating temperature and dissolved oxygen together, recommends that laboratory and field research be carried out to determine answers to the following questions:

1. What is the significance of daily and seasonal fluctuations in temperature and dissolved oxygen?
2. How rapid may changes be without exerting an adverse effect?
3. Does it matter if the fluctuations are out of phase with the natural cycle?
4. What are the effects of wide fluctuations above or below the daily mean and how much can temperatures be raised and dissolved oxygen concentrations lowered from natural conditions without harming the biota or causing a change in its makeup?
5. At what temperatures and dissolved oxygen levels will desired species be replaced by undesirable competitors?

6. What are the trade-offs relative to increased growth and total productivity versus parasites, disease and mortality of different life stages?
7. What levels of temperature and oxygen are harmful, tolerable and favorable for all the important species at all life stages, including egg, nymph, larvae, fry, etc.?
8. What are the effects of changes in daily and seasonal temperatures on migration, scope for activity and the toxicity of waste and materials?
9. What are the maximum temperature and minimum oxygen levels that can be tolerated for short periods without harm?
10. What are the allowable overall increases in temperatures at different seasons that do not produce undesirable effects on the biota?
11. What are the allowable and favorable levels of temperature and oxygen for all important species?
12. What are the requirements for low temperatures in the life cycle of important organisms?
13. What are the effects of stress due to pollutants on the temperatures which are lethal, tolerable or favorable?
14. What are the beneficial effects of the addition of heat?

The authors would like to stress the need for future investigators to conform to a standard methodology in determining temperature effects on the biota. For example, information on maximum lethal temperatures is rather useless unless simultaneous data are collected on the acclimating time, the length of time fish are exposed to temperature, the rate of change of temperature, the size of the animal, the condition of the organism, the salinity and dissolved oxygen concentrations and the concentration of ions which might be synergistic or antagonist to the effects of increased temperature (Doudoroff, 1957). Furthermore, even if the animals die or were dying at these temperatures, many experiments do not disclose if sublethal, irreversible physiological reactions had occurred well below the so-called upper lethal limit (de Sylva, 1969).

BIBLIOGRAPHY

Agersborg, H. P. K., 1930, "The Influence of Temperature on Fish", *Ecology*, 11, 136.

Agersborg, H. P. K., 1932, "The Relation of Temperature to Continuous Reproduction in the Pulmonate Snail". *Nautilus*, *45*, 121.

Alabaster, J. S., 1963, "Effects of Heated Effluents on Fish". *Int. Journal Air-Water Pollution*, *7*, 541.

Alabaster, J. S., 1962, "Effects of Heated Effluents on Fish". *Journal Water Pollution Control Federation*, *34*, #3, 207.

Alabaster, J. S., and Downing, A. L., 1958, "The Behavior of Road (*Rutilus rutilus* L.) in Temperature Gradients in a Large Outdoor Tank." *Proc. Indo-Pacific Fish. Coun.*, *3*, 49.

Allen, J. Frances, 1969, "Research Needs for Thermal Pollution Control". *Biological Aspects of Thermal Pollution*, edited by Peter A. Krenkel and Frank L. Parker, Vanderbilt University Press, 382-392.

Appourchaux, J., 1965, "Effects of Water Temperature on Aquatic Fauna and Flora". *L'Eau*, *52*, 377.

Badenhuizen, T. R., 1967, "Temperature Selected by *Tilapia mossambica* (Peters) in a Test Tank with a Horizontal Temperature Gradient." *Hydrobiologia*, *30*, 541.

Battaglia, B., and Lazzaretto, I., 1967, "Effect of Temperature on the Selective Value of Genotypes of the Copepod *Tisbe reticulata*." *Nature*, *215*, 999.

Beer, L. P., and Pipes, W. O., 1968, "A Practical Approach: Environmental Effects of Condenser Water Discharge in Southwest Lake Michigan". Report from Industrial Bio-Test Laboratory, Inc.

Beeton, A. M., 1961, "Environmental Changes in Lake Erie". Trans., American Fish Society, *90*, 153.

Berg, K., 1952, "On the O_2 Consumption of *Ancylidae* (Gastropoda) from an Ecological Point of View". *Hydrobiologia*, *4*, 225.

Black, E. C., 1953, "Upper Lethal Temperatures of Some British Columbia Freshwater Fishes." Journal of the Fisheries Research Board of Canada, *10*, 196-210.

Brett, J. R., 1944, "Some Lethal Temperature Relations of Algonauin Park Fishes". University of Toronto Stud. Biol. Ser., *52*, 1-49.

Brett, J. R., 1952, "Temperature Tolerance in Young Pacific Salmon, Genus *Oncorhynchus*". *Journal Fisheries Research Board, Canada*, *9*, 265.

Brett, J. R., 1956, "Some Principles in the Thermal Requirements of Fishes". *Quarterly Review of Biology*, 31, 75.

Brett, J. R., 1958, "Implications and Assessments of Environmental Stress". *The Investigations of Fish Power Problems*, H. R. MacMillan Lectures in Fisheries, Vancouver, B. C.

Brett, J. R., 1960, "Thermal Requirements of Fish - Three Decades of Study, 1940-1970". Biological Problems in Water Pollution, Tech. Report No. W60-3.

British Ministry of Agriculture, Fisheries and Food, 1961a, "Salmon and Freshwater Fisheries Res. Report." Water Pollution Abstract No. 71, *34*.

British Ministry of Agriculture, Fisheries and Food, 1961b, "Salmon and Freshwater Fisheries Res. Report, Water Pollution Abstract No. 1192, *34*.

Brock, T. D., 1967, "Microorganisms Adapted to High Temperatures". *Nature*, *214*, 622.

Brown, V. M., Jordan, D. H. M., and Tiller, B. A., 1967, "The Effect of Temperature on the Acute Toxicity of Phenol to Rainbow Trout in Hard Water". *Water Research*, *427*, 587-94.

Bullock, T. H., 1955, "Compensation for Temperature in the Metabolism and Activity of Poikilotherms." *Biology Review*, *30*, 311.

Burdick, G. E., Lipshuetz, M., Dean, H. J., and Harris, E. J., 1954, "Lethal Oxygen Concentrations for Trout and Smallmouth Bass." *New York Fish and Game Journal*, *1*, 84.

Burnson, B., 1938, "Seasonal Temperature Variations in Relation to Water Treatment." *Journal of American Water Works Association*, 30, 793.

Cairns, J., Jr., 1956a, "Effects of Increased Temperatures on Aquatic Organisms", *Industrial Wastes*

Cairns, J., Jr., 1956b, "Effects of Heat on Fish." *Industrial Wastes*, *1*, 180.

Cairns, J., Jr., 1967, "The Use of Quality Control Techniques in the Management of Aquatic Ecosystems", Water Resources Bulletin, 3, No. 4.

Campbell, L. S., 1960, "Inventory of Species Present in Lake Colorado City, near Colorado City, TExas." Report on Dingell-Johnson Project F5R7 to Texas Game and Fish Commission.

Campbell, R. S., Whitley, J. R., and Brezina, E. R., 1966, "Water Quality Alteration Through Acid and Heat Pollution in a 1500 Acre Reservoir." Project Report No. 1, Water Resources Research Center, University of Missouri.

Clark, J. R., 1969, "Thermal Pollution and Aquatic Life". Sci. Amer., 220, 19.

Cocking, A. W., 1959a, "The Effects of High Temperatures on Roach (Rutilus rutilus), I. The Effects of Constant High Temperatures." Journal, Exp. Biol., 36, 203.

Cocking, A. W., 1959b, "The Effects of High Temperatures on Roach (Rutilus Rutilus), II. The Effects of Temperature Increasing at a Known Constant Rate." Journal, Exp. Biol, 36, 217.

Coutant, C. C., 1962, "The Effect of a Heated Water Effluent upon the Macroinvertebrate Riffle Fauna of the Delaware River." Penn. Acad. Science, 37, 58.

Dallinger, W. H., 1887, "The President's Address". Journal of Royal Microscophical Society, Ser. 2, 7, 185.

Davenport, C. B., and Castle, W. E., 1895, "Studies in Morphogenesis". Arch. F. Entw., 2, 227.

Dendy, J. S., 1945, "Fish Distribution, Norris Reservoir, Tennessee, 1943. II. Depth Distribution of Fish in Relation to Environmental Factors." Report to Reelfoot Lake Biological Sta., Journal Tennessee Academic Science, 20, 114.

DeRoche, S. E., and Bond, L. H., 1955, "Lake Trout of Cold Stream Pond, Enfield, Maine." Trans. American Fisheries Society, 85, 257.

De Silva, D. P., 1969, "Theoretical Considerations of the Effects of Heated Effluents on Marine Fishes." Biological Aspects of Thermal Pollution, edited by P. A. Krenkel and F. L. Parker, Vanderbilt University Press.

Dorris, T. C., Copeland, B. J., and Laver, G. J., 1963, "Limnology of the Middle Mississippi River. IV. Physical and Chemical Limnology of River and Chute." Limnology and Oceanography, 8, 79.

Doudoroff, P., 1938, "Reactions of Marine Fishes to Temperature Gradients." Biology Bulletin, 74, 494.

Doudoroff, P., 1957, "Water Quality Requirements of Fishes and Effects of Toxic Substances", The Physiology of Fishes, edited by Margaret E. Brown, Academic Press, New York, N. Y., 403-443.

Dryer, W., and Benson, N. G., 1957, "Observations on the Influence of the New Johnsonville Steam Plant on Fish and Plankton Populations." Proc. 10th Annual Conference of the Southeastern Association of Game and Fish Commissions.

Dzyan, Yao-Tsin, 1962, "Changes in the Temperature Preferences of Certain Species of Sturgeon at Varying Levels of Food Supply." Referat. Zhur. Biol. 1961, No. 4D74; Sport. Fish. Abstracts, 7.

Ellis, M. M., 1937, "Detection and Measurement of Stream Pollution." Bulletin, U. S. Bureau of Fisheries, 48, 365.

Federal Water Pollution Control Administration, 1967, "Temperature and Aquatic Life." Technical Advisory and Investigations, Laboratory Investigations, Series No. 6

Ferguson, R. G., 1958, "The Preferred Temperature of Fish and Their Midsummer Distribution in Temperate Lakes and Streams." Journal Fisheries Research Board of Canada, 15, 607.

Fisher, K. C., and Scott, G. W., 1942, "On the Physiological Mechanism of Temperature Selection by Fish", The Collecting Net, 17, 48.

Fowler, H. W., 1940, "List of Fishes Recorded from Pennsylvania." Bull. Commonwealth of Pennsylvania, Board of Fish Comm.

Fry, F. E. J., 1958, "Temperature Compensation," American Rev. Physiol., 20, 207.

Fry, F. E. J., Brett, J. R., and Clawson, G. H., 1942, "Lethal Limits of Temperature for Young Goldfish." Review Canadian Biol., 1, 50.

Fry, F. E. J. and Hart, J. S., 1948, "The Relation of Temperature to Oxygen Consumption in the Goldfish." Biology Bulletin, 94, 66-77.

Fry, F. E. J., Hart, J. S., and Walker, K. F., 1946, "Lethal Temperature Relations for A Sample of Young Speckled Trout, Salvelinus fontinalis." University of Toronto Studies Biology, No. 54.

Gameson, A. L. H., Gibbs, J. W., and Barrett, M. S., 1959, "A Preliminary Temperature Survey of a Heated River." Water and Water Engineering, London, 63, No. 755, 13.

Gammon, K. M., 1968, "Planning Cooling Water for Power Stations." Fourth Annual Conf. on Water Pollution, Prague, Pergamon Press Ltd.

Garside, E. T., and Tait, J. S., 1958, "Preferred Temperature of Rainbow Trout (*Salmogaindneri*, Richardson)and Its Unusual Relationship to Acclimation Temperature." *Canadian Journal of Zoology*, 36, 563.

Graham, J. M., 1949, "Some Effects of Temperature and Oxygen Pressure on the Metabolism and Activity of the Speckled Trout, *Salvelinus Fontinalis*". *Canadian Journal of Research*, Series D, 27.

Gunter, G., 1957, "Temperature", *Ecology, in Marine Ecology and Paleoecology*, 1, chap. 8, J. W. Hedgepeth, Ed., Geological Society of America, Memoir 67.

Gunther, E. R., 1936, "A Report on Oceanographical Investigations in the Peru Coastal Current." *Discovery Reports*, 13, 107.

Halcrow, K., 1963, "Acclimation to Temperature in the Marine Copepod, *Calanus finmarchicus* (Gunner)." *Limnology and Oceanography*, 8, 1.

Hathaway, E. S., 1928, "Quantitative Study of the Changes Produced by Acclimatization in the Tolerance of High Temperatures by Fishes and Amphibians." *Bull. U. S. Fisheries*, 43, 169.

Hokanson, K. E. F., 1969a, "Aquatic Life Temperature Requirements". *FWPCA Presentations, Orsanco Engineering Committee, Section D.*, 16.

Kokanson, K. E. F., 1969b, "Biological Effects of Heated Waters." Paper presented at Technical Seminar on Thermal Pollution, Ada, Okla.

Hubbs, C., 1964, "Effects of Thermal Fluctuations on the Relative Survival of Greenthroat Darter Young from Stenothermal and Eury-Thermal Waters." *Ecology*, 45, 376.

Hutchison, L., 1947, "Analysis of the Activity of the Fresh Water Snail, *Viviparous malleatus* (Reeve)." *Ecology*, 28, 335.

Hynes, H. B. N., 1960, *Biology of Polluted Waters*, Liverpool University Press, 71.

Iezzi, T., Filson, J. A., and Myers, C. S., 1952, "Effects of Temperature Changes and Temperature Levels on *Lepomis macrochirus macrochirus* (Bluegill Sunfish) and on *Salmofario* (Brown Trout)." Pennsylvania Department of Public Health, Industrial Wastes Division.

Jones, J. R. E., 1964, "Fish and River Pollution", Butterworth & Co., Ltd., London.

Jones, S. Leary, 1966, Personal Communication.

Kennedy, V. S., and Mihursky, J. A., 1967, "Bibliography on the Effects of Temperature in the Aquatic Environment." Contribution No. 326, Natural Resources Institute, University of Maryland.

Krenkel, P. A., Cawley, W. A., and Minch, V. A., 1965, "The Effect of Reservoirs on Waste Assimilative Capacity," Journal, Water Pollution Control Federation.

Krenkel, P. A., and Parker, F. L., 1969, "Engineering Aspects, Sources, and Magnitude of Thermal Pollution." Biological Aspects of Thermal Pollution, edited by P. A. Krenkel and F. C. Parker, Vanderbilt University Press, 10-52.

Loeb, J., and Wasteneys, H., 1912, "On the Adaptation of Fish (Fundulus) to Higher Temperatures." Journal, Experimental Zoology, 12, 543.

Mackenthun, K. M., Ed., 1967, "Temperature and Aquatic Life." Lab. Invest. No. 6, Tech. Advisory and Investigations Branch, Water Pollution Control Administration, U. S. Department of the Interior, Cincinnati, Ohio.

Mann, K. H., 1965, "Heated Effluents and Their Effects on the Invertebrate Fauna of Rivers." Proc. Society Water Treatment Examination, 14, 45.

Mantleman, I. I., 1960, "Distribution of the Young of Certain Species of Fish in Temperature Gradients." Trans. Ser. No. 257, Journal, Fisheries Research Board of Canada, Biol. Sta. Nanaimo, British Columbia.

Markowski, S., 1959, "The Cooling Water of Power Stations: A New Factor in the Environment of Marine and Freshwater Invertebrates." Journal of Animal Ecology, 28, 243.

Mason, K. M., 1962, "Heated Discharges - Their Effects on Streams." Report by the Advisory Committee of Stream Temperatures to the Pennsylvania Sanitary Water Board, Pub. No. 3.

McKee, Jack E., and Wolf, Harold W., 1963, Water Quality Criteria, The Resources Agency of California State Water Quality Control Board, Pub. No. 3-A, Second Edition.

Mihursky, J. A., and Kennedy, V. S., 1967, "Water Quality Criteria to Protect Aquatic Life." American Fisheries Society, Special Pub. No. 4, 20-32.

Mihursky, J. A. and Cronin, L. Eugene, 1967, "Progress and Problems in Thermal Pollution in Maryland." Contribution No. 344, Natural Resources Institute, University of Maryland, presented at Maryland Water Quality Symposium.

Moore, E. W., 1958, "Thermal Pollution of Streams." Industrial Engineering Chemistry, 50, 87A.

Moore, W. G. 1942, "Studies on the Oxygen Requirements of Certain Freshwater Fishes." Ecology, 23, 319.

Mount, D. I., 1969a, "Developing Thermal Requirements for Freshwater Fishes." Biological Aspects of Thermal Pollution, edited by P. A. Krenkel and F. L. Parker, Vanderbilt University Press, 140-147.

Mount, D. I., 1969b, "Research on Temperature Effects on Fishes." Presented at Eighth Annual Environmental and Water Resources Engineering Conference, Nashville, Tenn.

National Technical Advisory Committee, 1968, "Water Quality Criteria", Report to the Secretary of Interior, U. S. Government Printing Office, Washington, D.C.

Nickum, J. G., 1967, "Some Effects of Sudden Temperature Changes Upon Selected Species of Freshwater Fishes." Thesis, Southern Illinois University; Dissertation Abstracts, 27, B, 3344 (1967).

Patrick, Ruth, 1949, "A Proposed Biological Measure of Stream Conditions, Based on a Survey of the Conestoga Basin, Lancaster County, Pennsylvania." Proc. Academy of Natural Sciences, Philadelphia 101: 277-341.

Patrick, Ruth, Hohn, M.H., and Wallace, J. H., 1954, "A New Method for Determining the Pattern of Diatom Flora." Notulae Naturae, Academy Natural Sciences, Philadelphia, No. 259, 12.

Pitt, T. K., Garside, E. T., and Hepburn, R. L., 1956, "Temperature Selection of the Carp (Cyprinus carpio Linn.)." Canadian Journal Zoology, 34, 555.

Raney, Edward C., and Menzel, Bruce W., 1967, "Heated Effluent and Effects on Aquatic Life with Emphasis on Fishes." Bibliography Philadelphia Electric Company and Ichthyological Associates, Bull. No. 1.

Rao, Kandula Pampapathi, 1967, "Biochemical Correlates of Temperature Acclimation." Molecular Mechanisms of Temperature Adaptation, edited by A. S. Troshin, American Association for the Advancement of Science, Pub. No. 84, 227-244.

Segal, E., 1956, "Microgeographic Variation as Thermal Acclimation in an Intertidal Molusc." Biology Bulletin, 111, 129.

Shelford, V. E., 1929, "Laboratory and Field Ecology". Williams and Wilkens Co., Baltimore, Md.

Silliman, R. P., 1943, "Thermal and Diurnal Changes in the Vertical Distribution of Eggs and Larvae of the Pilchard (Sardinops caerulea)." Journal Marine Research, 5, 118.

Slack, K. V., and Clark, F. E., 1965, "Patterns of Dissolved Oxygen in a Thermally Loaded Reach of the Susquehanna River, Pennsylvania." U. S. Geological Survey Professional Paper 525-C, C193.

Sprague, J. B., 1963, "Resistance of Four Freshwater Crustaceans to Lethal High Temperatures and Low Oxygen." Journal Fisheries Research Board, Canada, 20, 387.

Strickland, J. B., 1969, "The Effects of Heated Discharges on Marine Zooplankton." Biological Aspects of Thermal Pollution, Edited by P. A. Krenkel and F. L. Parker, Vanderbilt University Press.

Sullivan, C. M., and Fisher, K. C., 1953, "Seasonal Fluctuations in the Selected Temperature of Speckled Trout, Salvelinus fontinalis (Mitchill)." Journal Fisheries Research Board, Canada, 10, 187.

Sumner, F. B., and Doudoroff, P., 1938, "Some Experiments Upon Temperature Acclimatization and Respitory Metabolism in Fishes." Biology Bulletin, 74, 403.

Tarzwell, C. M., 1956, "Water Quality Criteria for Aquatic Life." Trans. Seminar Biol Problems Water Poll., U. S. Public Health Service, 246.

Tennessee Valley Authority, Water Quality Branch, 1967, "Thermal and Biological Studies in the Vicinity of Widows Creek Steam Plant." TVA, Chattanooga, Tenn.

Thoman, J. R., 1969, Personal Communication.

Threinen, C. W., 1958, "Cause of Mortality of a Midsummer Plant of Rainbow Trout in a Southern Wisconsin Lake, with Notes on Acclimation and Lethal Temperatures." Progressive Fisheries Culturist, 20, 27.

Trembley, F. J., 1961, "Research Project on Effects of Condenser Discharge Water on Aquatic Life." Progress Report, 1960, The Institute of Research, Lehigh University.

Trembley, F. J. 1960, "Research Project on Effects of Condenser Discharge Water on Aquatic Life." Progress Report, 1956-59, The Institute of Research, Lehigh University.

Troshin, A. S., Ed., 1967, "The Cell and Environmental Temperature." Proc. Int. Symposium on Cytoecology (Leningrad), Pergamon Press, New York, N. Y.

Tyler, A. V., 1966, "Some Lethal Temperature Relations of Two Minnows of the Genus Chrosomus." Canadian Journal Zoology, 44, 349.

Usinger, R. L., 1956, "Aquatic Insects of California." University of California Press.

VonBrand, T., Nolan, M. O., and Mann, E. R., 1948, "Observations on the Respiration of Australorbis glabratus and Some Other Aquatic Snails." Biology Bulletin, 95, 199.

Whitney, R. J., 1939, "The Thermal Resistance of Mayfly Numphs from Ponds and Streams." Journal Experimental Biology, 16, 374.

Wurtz, C. B., 1961, "The Effects of Heat Discharges on Aquatic Life and Water Use." ASME Paper 61-2H-142.

Wurtz, C. B., and Dolan, T., 1960, "ABiological Method Used in the Evaluation of Effects of Thermal Discharge in the Schuylkill River." Proc 15th Industrial Waste Conference, Purdue University, 461.

Wurtz, C. B., and Renn, C. E., 1964, "Water Temperatures and Aquatic Life." Edison Electric Institute Research Project No. 49, The Institute of Cooperative Research of the Johns Hopkins University.

CHAPTER IV - 1

EFFECTS OF HEATED DISCHARGES ON WATER QUALITY AND WASTE ASSIMILATION

Senator Muskie (1967) has stated that: "It is the opinion of the Senate Subcommittee on Air and Water Pollution that excessive heat is as much a pollutant as municipal wastes or industrial discharges". This chapter will indicate why this is a correct statement.

A. Stratification in Impounded Waters

While the stratification process in reservoirs and lakes is well known, the resulting changes in water quality are not. The changes are becoming increasingly important because of the growth of complex water resource systems.

At the end of a winter season, the impounded water is usually of a fairly uniform quality and has a relatively low temperature. At the onset of higher atmospheric temperatures, the surface water and the incoming water temperatures are raised and this lighter water tends to "float" on the colder and denser water already in the lake.

Three definite strata may be formed, the surface stratum or epilimnion, the lower stratum or hypolimnion, and a transition zone called the thermocline, where the maximum rate of change of temperature with depth occurs. In the southeast the thermocline persists from about April to November and is approximately 10 to 20 feet in thickness. In a deep reservoir the epilimnion may be approximately 30 to 50 feet in thickness and the hypolimnion will usually extend to the reservoir bottom.

These conditions may exist until autumn, when the lake begins to lose heat more quickly than it is absorbed. As the water becomes cooler and more dense, the thermocline sinks, unstable conditions occur and the reservoir mixes or overturns. In climates where the water temperature goes below 4°C, two turnovers may occur per year.

Many impounded waters circulate completely but some circulate only partially, these lakes being called meromictic by limnologists. This stable, lower layer can be caused by either an accumulation of dissolved or suspended solids in the water and may render this lower portion of the lake unsuitable for a water supply.

A typical reservoir profile as described above is shown on Figure IV-1 as taken from the work of Kittrell (1959).

1. Discharges of Differing Density

Density currents, density flows, under-flows, overflows, and interflow are all synonomous with stratified flow. As defined by the National Bureau of Standards (Anon., 1938), "A density current is the movement, without loss of identity by turbulent mixing at the bounding surfaces, of a stream of fluid under, through, or over a body of fluid, with which it is miscible and the density of which varies from that of the current, the density difference being a function of the differences in temperature, salt content, and/or silt content of the two fluids."

The various forms of a density current are as depicted on Figure IV-2, the overflow, the interflow, and the underflow. Each of these currents may affect water quality in an adverse manner. Probably the most important form of a density current to the thermal pollution problem

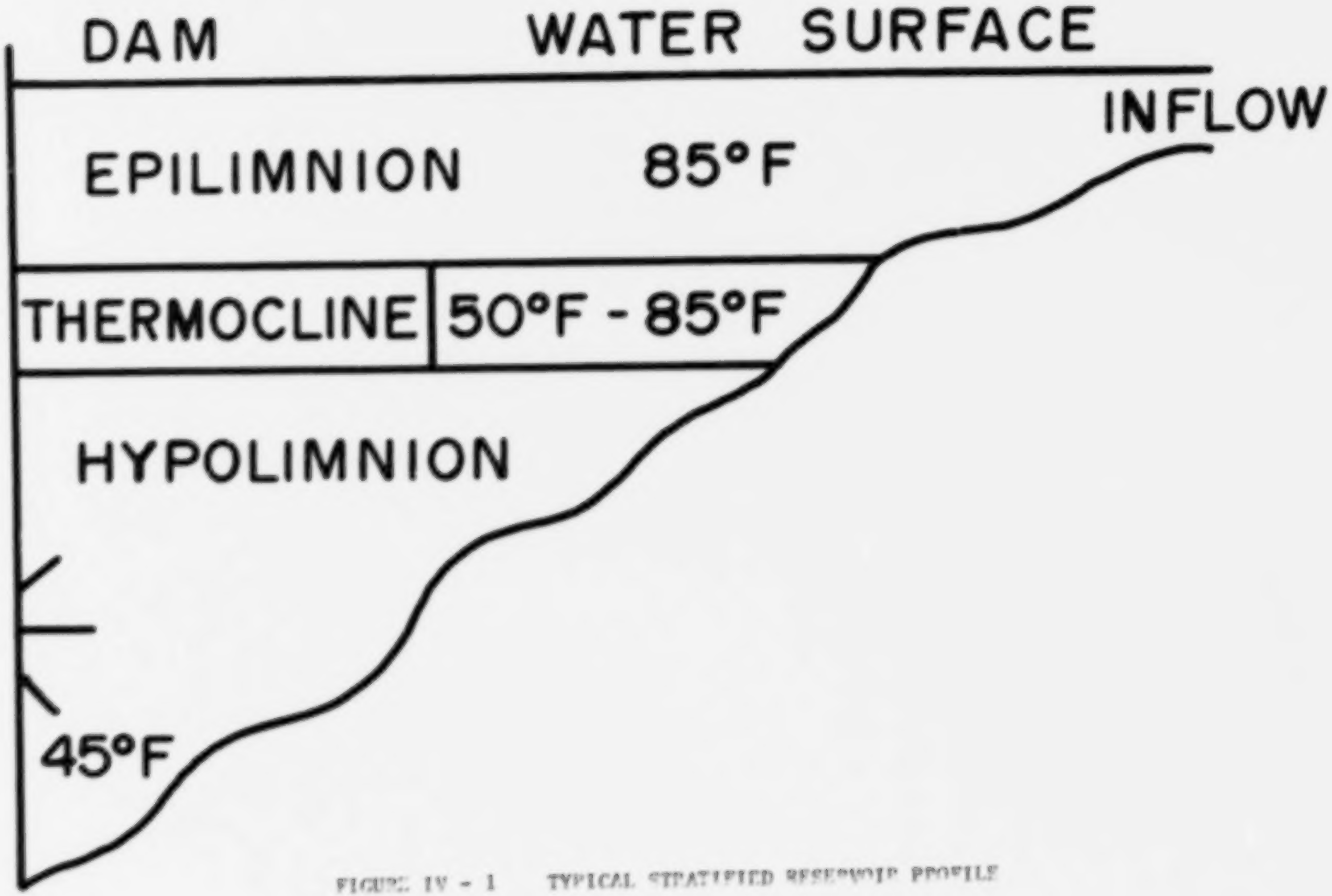

DAM
WATER SURFACE
INFLOW
EPILIMNION
85°F
THERMOCLINE
50°F - 85°F
HYPOLIMNION
45°F

FIGURE IV - 1 TYPICAL STRATIFIED RESERVOIR PROFILE

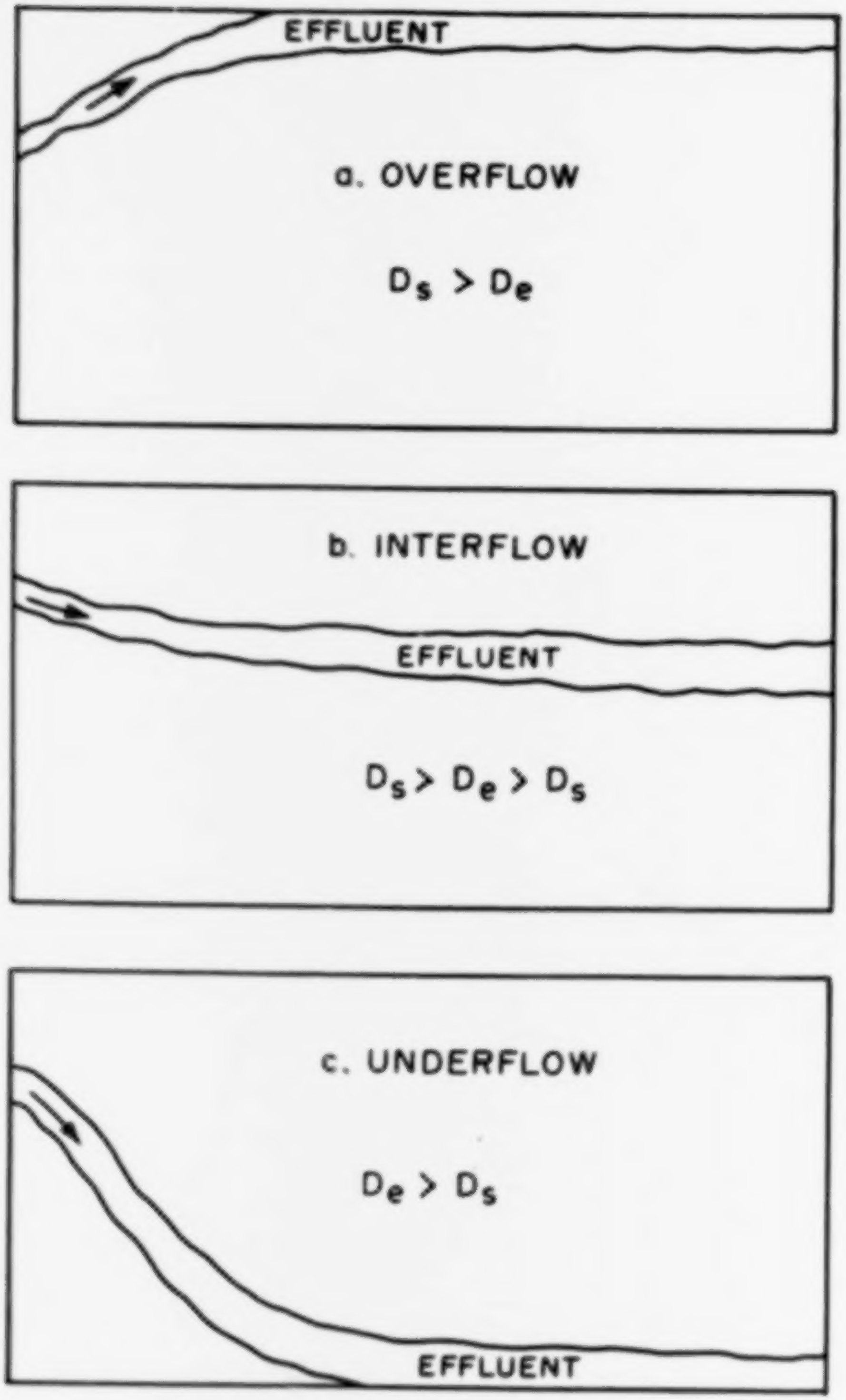

EFFLUENT
a. OVERFLOW
$D_s > D_e$
b. INTERFLOW
EFFLUENT
$D_s > D_e > D_s$
c. UNDERFLOW
$D_e > D_s$
EFFLUENT

FIGURE IV - 2 DIFFERENT FORMS OF DENSITY CURRENTS

is the overflow because of its occurrence in the discharge of cooling waters.

Stratified flow has been observed when $\Delta\rho/\rho \geq 0.005$, where ρ is the fluid density and $\Delta\rho$ is the density differential between the fluid layers (American Society of Civil Engineers Committee on Sedimentation, 1963). It is interesting to note that this condition is satisfied with water temperatures of 31°C and 32.5°C.

In order to illustrate these various forms of density currents, the following examples, each with a possible deleterious effect on water quality, are presented.

a. The Underflow:

Underflows can be caused by the discharge of colder, more dense water from an upstream stratified reservoir or by water containing excessive suspended or dissolved solids. Underflows caused by highly turbid waters were first noted on Lake Mead while the underflow caused by the upstream release of hypolimnetic water frequently occurs in TVA reservoirs. Fish kills have been reported to have occurred downstream from Fort Loudon Dam purportedly caused by the low dissolved oxygen content resulting from the release of cold hypolimnion water (Jones, 1964). Figure IV-3 shows a schematic diagram depicting the flow regime caused by an underflow as presented by Elder (1964). Two different flow regimes are noted; the lower strata, bounded by the channel bottom and the interface with the velocity profile approximating that of distorted pipe flow, and the upper layer, bounded by the interface and the atmosphere and behaving like free surface flow.

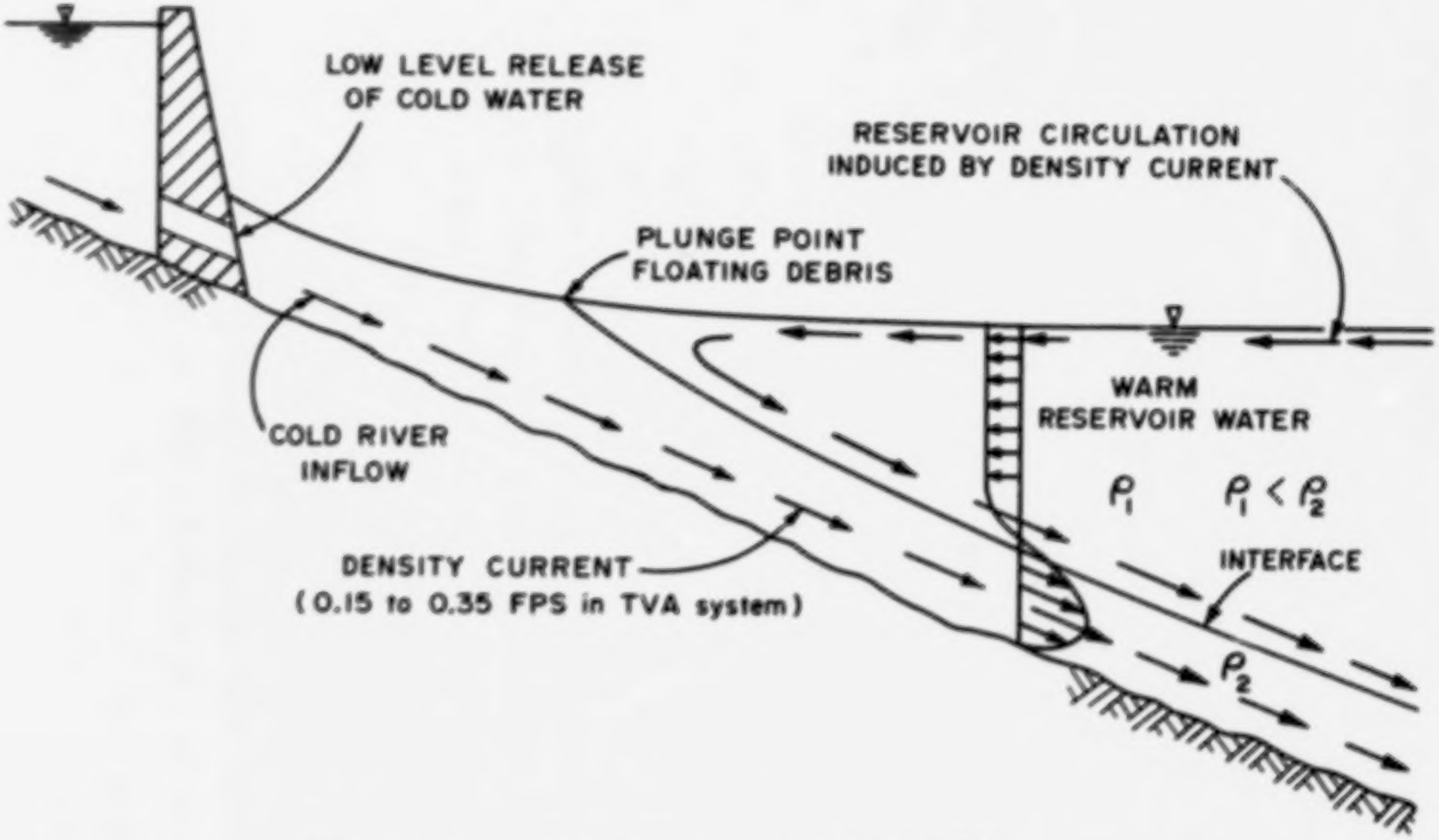

LOW LEVEL RELEASE
OF COLD WATER
RESERVOIR CIRCULATION
INDUCED BY DENSITY CURRENT
PLUNGE POINT
FLOATING DEBRIS
WARM
RESERVOIR WATER
COLD RIVER
INFLOW
ρ_1
$\rho_1 < \rho_2$
INTERFACE
DENSITY CURRENT
(0.15 to 0.35 FPS in TVA system)
ρ_2

FIGURE IV - 3 RESERVOIR WITH DENSITY UNDERFLOW

Water quality may be adversely affected by a flow reversal in the upper layers of the reservoir. Under these conditions, should the water pollution control plant discharge be located downstream or upstream from the water treatment plant intake?

b. The Interflow

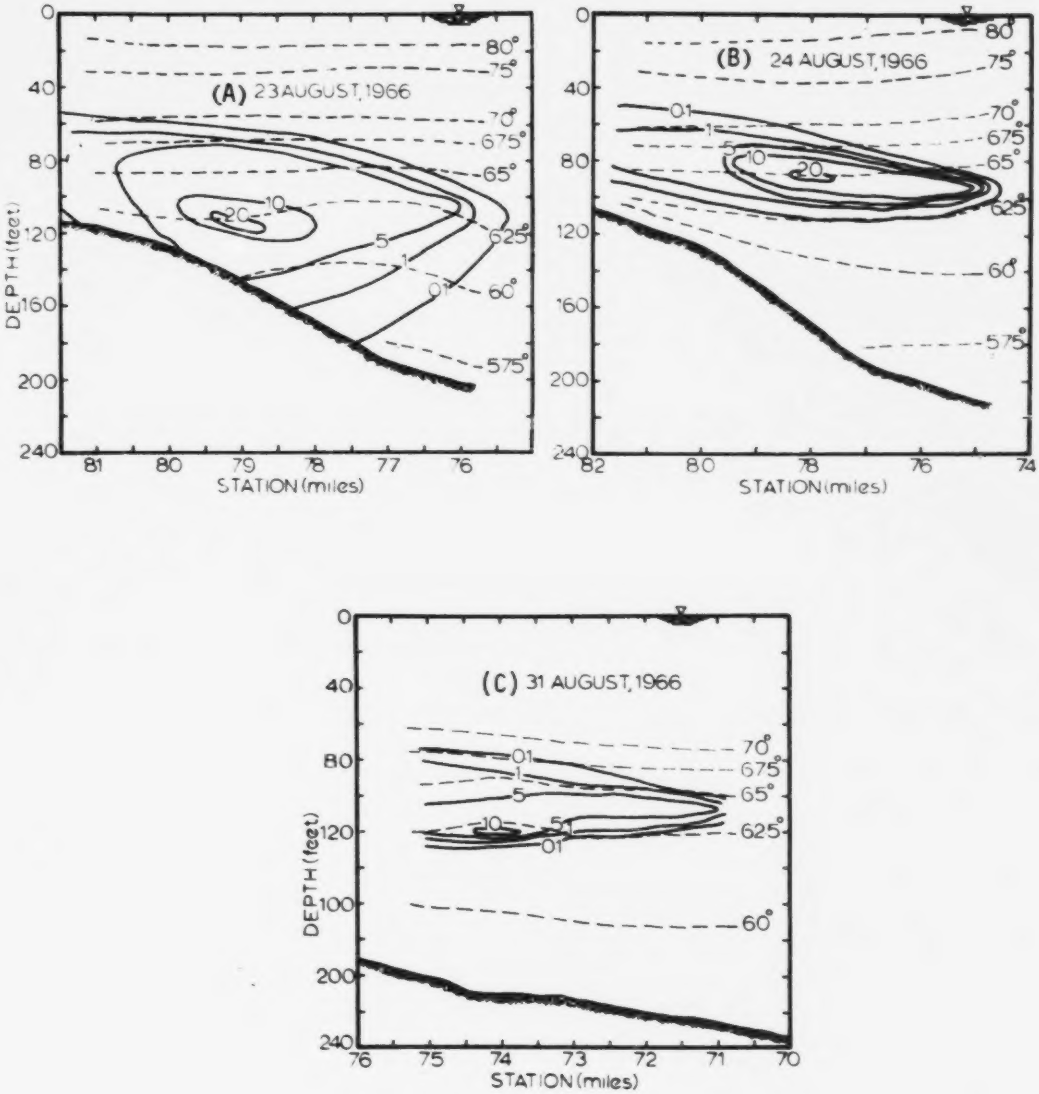
The interflow results from the discharge of a fluid of an intermediate density into a stratified flow regime. Figure IV-4 shows labeled Nantahala River 59°F water as it became an interflow at the appropriate density level. The 4°F rise in temperature was attributed to mixing and surface heating in the shallow, upper reaches of the reservoir (Krenkel, et al., 1969).

Another example of an interflow is the process of selective withdrawal as shown idealized on Figure IV-5. Under unstratified conditions, one would withdraw water from all levels of the reservoir; however, under stratified flow conditions, withdrawal is from a pre-selected layer, depending on the level of the water intake.

If interflows are heavily polluted with organic material, do reservoirs satisfactorily assimilate the waste? Since this hypothetical waste would contribute to the hypolimnion deficit, would not the pollutional effects only have been relocated and delayed? The sampling techniques for this situation also pose some interesting questions.

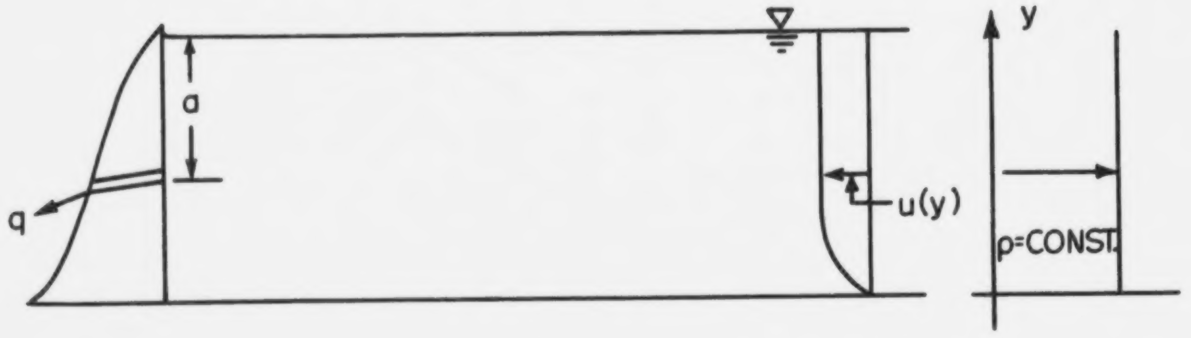
c. The Overflow:

The overflow is caused by the discharge of lighter density water and is most commonly observed when cooling waters are discharged into a receiving water at its surface. While the heat is obviously dissipated more rapidly with this means of discharge than if the cooling

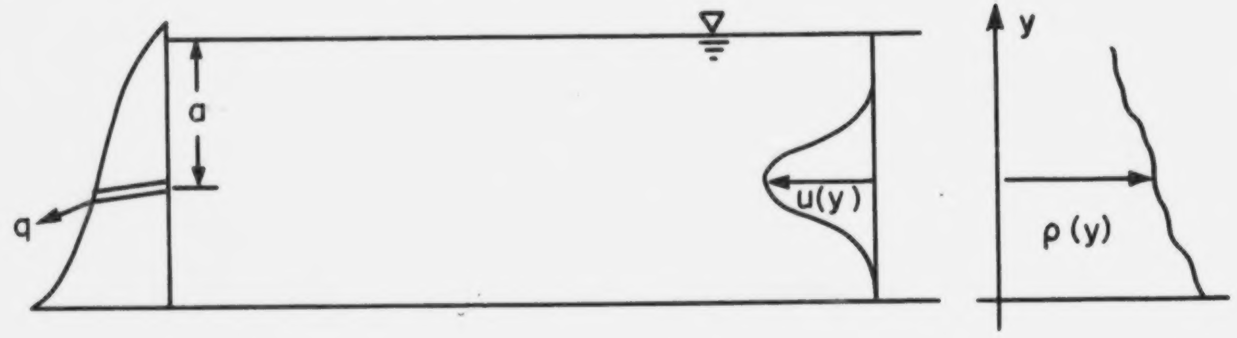


MOVEMENT OF DYE CLOUD THROUGH FONTANA RESERVOIR

FIGURE IV - 4 TAGGED INTERFLOW THROUGH FONTANA RESERVOIR


a
q
u(y)
y
ρ=CONST.

(A) Withdrawal from full depth in a homogeneous fluid.



(B) Selective withdrawal in a stratified field.

FIGURE IV - 5 SELECTIVE WITHDRAWAL AS AN INTERFLOW

water were completely mixed with the receiving water, the higher temperature of the resulting stratified flow may be totally unacceptable from the water quality standpoint.

B. Effects of Stratified Flow on Water Quality

1. Dissolved Oxygen:

Water containing organic material entering a stratified reservoir will deplete the oxygen resources of the reservoir due to biological respiration. In the epilimnion, mixing by wind currents, photosynthesis and sedimentation may render the epilimnetic water satisfactory. However, in the hypolimnion, oxygen removed by biological action is not replaced, algae cannot grow, essentially no vertical mixing takes place and the products of sedimentation from the epilimnion may add additional organic load. The net result is a depletion of the dissolved oxygen resources, thus making septic conditions possible.

If this hypolimnetic water with its low oxygen content is discharged from the dam, fish life may not be supported for several miles downstream, a lower waste assimilation capacity may exist and in effect, the dam may be considered as being equivalent to a large BOD concentration.

2. Iron and Manganese:

If there is a low oxidation-reduction potential at the mud-water interface, conditions amenable to the dissolution of iron and manganese into the hypolimnetic waters will occur. The mechanism is not clear; however, if the oxides of these metals are present in the bottom muds, troublesome concentrations may appear in the water under reduced environmental conditions.

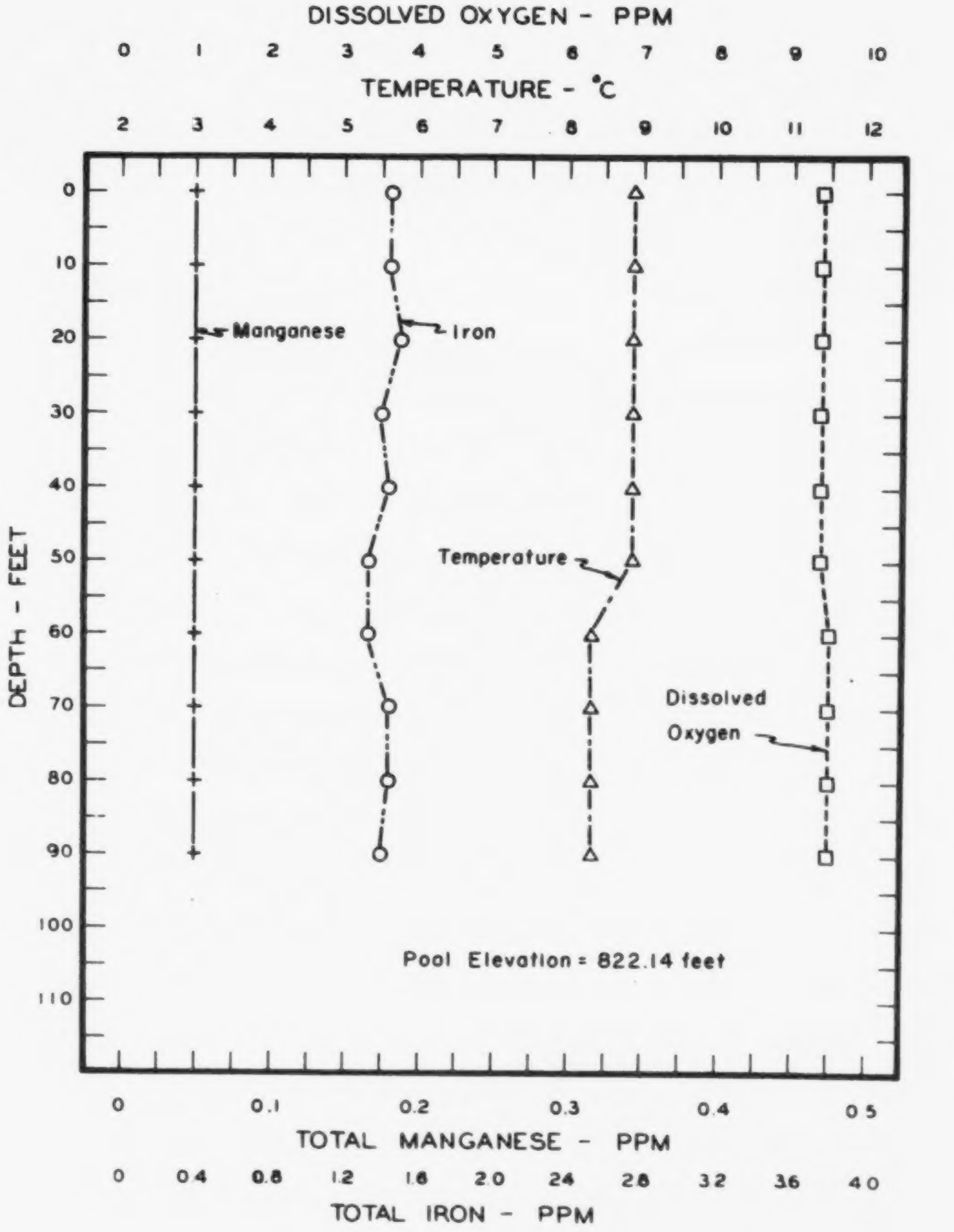
3. Temperature:

The temperature differential in stratified lakes can be quite significant. Since a major water use in the United States is for cooling purposes, it is obvious that this cooler water is highly desirable for condenser cooling for steam-electrical generation purposes. In fact, the use of this colder water by construction of an underwater dam at the TVA Kingston Steam Plant was reported to have saved TVA $155,000 in operating costs for the year 1956 alone, which was one-third the cost of the dam (Elder and Daugherty, 1956).

Figures IV-6 and IV-7 show the conditions existing in Allatoona Reservoir during completely mixed conditions and under a stratified flow regime. Note that in the summer, the temperature varies from over 27°C at the surface to approximately 17°C at the reservoir bottom. Difficulties are encountered from the low oxygen and high iron and manganese concentrations as the water intake is from the lower levels.

C. Waste Assimilative Capacity

If the discharge from a power plant is in the form of an overflow, mixing between the upper and lower layers is inhibited, thus minimizing oxygen replacement and self-purification in the lower layer. Due to lack of mixing, organic wastes discharged into the lower layer do not have access to the oxygen in that portion of the stream flowing in the upper layer. Thus, there is less dissolved oxygen, less dilution water and a more concentrated organic load in the lower layer leading to an acceleration of the dissolved oxygen depletion. The net result may be



DISTRIBUTION OF WATER QUALITY PARAMETERS IN ALLATOONA RESERVOIR ON 15 JANUARY 1965

FIGURE IV - 6 DISTRIBUTION OF WATER QUALITY PARAMETERS UNDER ISOTHERMAL CONDITIONS

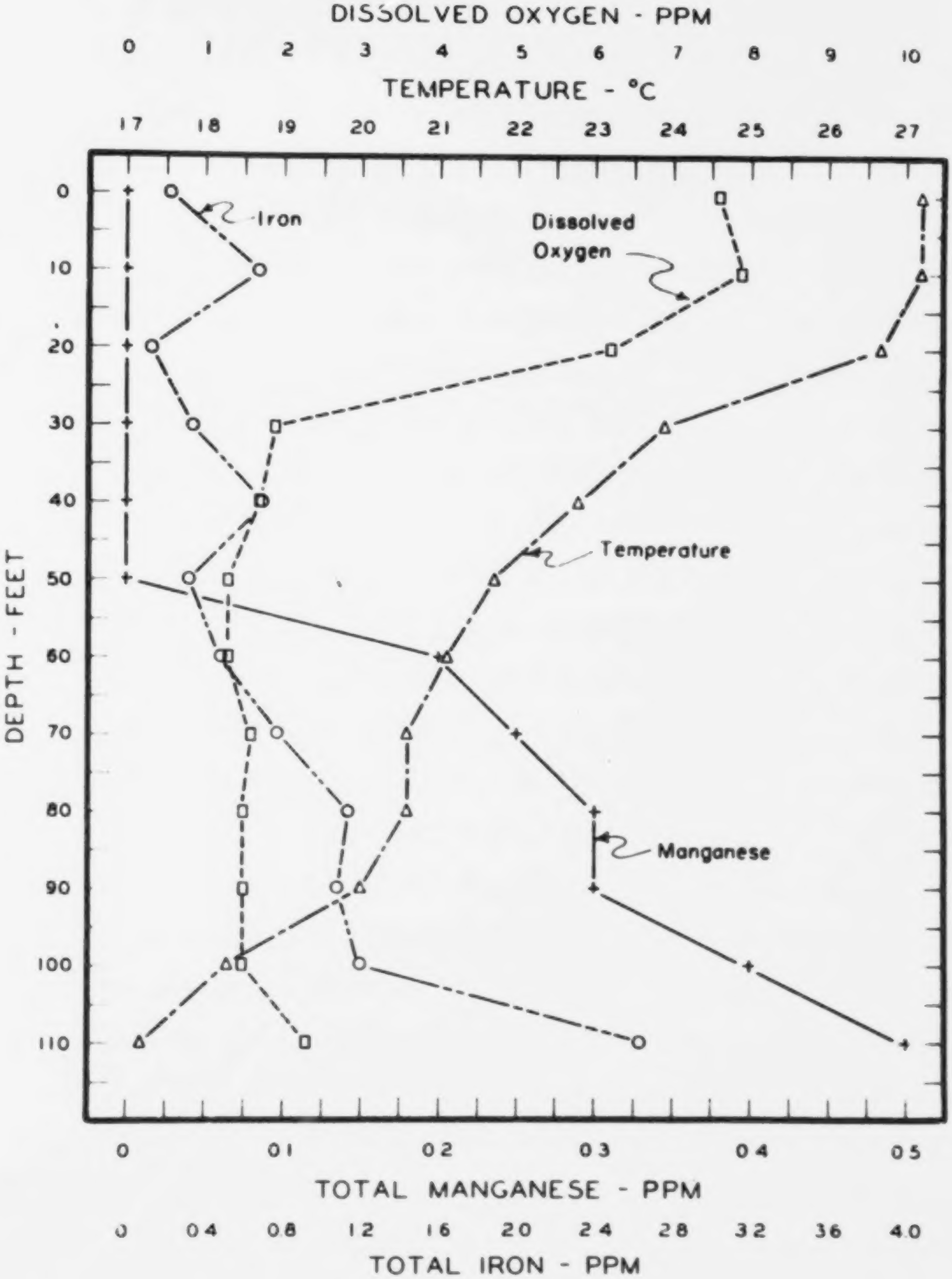


FIGURE IV - 7 REDISTRIBUTION OF WATER QUALITY PARAMETERS UNDER STRATIFIED CONDITIONS

a considerable reduction in the waste assimilative capacity of the receiving water.

If the heated discharge is completely mixed with the receiving water, some of the above mentioned effects are eliminated; however, the rise in temperature still causes a decrease in the ability of water to hold dissolved oxygen, an increase in the metabolic activity of organisms, an increased rate of Biochemical Oxygen Demand exertion and a possible reduction in waste assimilative capacity.

The discussion as to whether the heated water should be discharged as a layer or completely mixed with the receiving water must be based on conditions existing in the receiving water and the amount of heat to be dissipated. Obviously, the heat will be dissipated more quickly if it is concentrated in a lesser volume of water. The effects of the resulting stratified flow on the biota are not so obvious, however. While it is true that fish will have passage through the cool, lower layers of water, the fish cannot utilize this route if the water is devoid of oxygen.

Another possible route for heated water effluents is to "hug" the shoreline and not gain entry into the major portion of the river flow for many miles downstream. Such a situation was noted in Poland where separation of flow existed for over ten kilometers downstream from the confluence of the two rivers (Krenkel, 1967).

An example of the change in river waste assimilation capacity caused by both temperature and impoundment was presented by Krenkel et al. (1965). A paper mill of the Georgia Kraft Company, which had previously satisfactorily discharged its waste effluent into the free-flowing Coosa River, must now discharge into the backwater of a downstream impoundment and receive its flow as regulated by a peaking hydro-electric power plant upstream. The daily fluctuation in discharge may range from 200 to 7800 cfs. In addition, a steam electric generating plant, with a capacity of 300,000 kilowatts, has located adjacent to the mill, and the condenser water raises the temperature of the stream several degrees.

The effects of temperature on the stream self-purification process is demonstrated by Figure IV-8 which shows the variation of the rate constants k_1 (de-oxygenation) and k_2 (reaeration) with respect to temperature. Examination of this relationship demonstrates that an increase in temperature causes a considerable increase in k_1. While k_2 also increases with increasing temperature, it is negated by the combination of a lesser dissolved oxygen content and a greater rate of change of k_1 with temperature.

The overall effects of the impoundment on the rate of oxygen recovery is demonstrated by the lower curve, which depicts the reaeration rate constant under existing, impounded conditions. Note that, while k_1 at a given temperature is unchanged, the value of k_2 at any temperature is significantly reduced.

In order to illustrate the effect of temperature on the waste assimilative capacity of the Coosa River, field data were used to obtain Figure IV-9 which depicts the oxygen balance in the Coosa River prior to the previously mentioned water resources developments. Note that under these conditions, the Coosa River easily assimilated 28,000

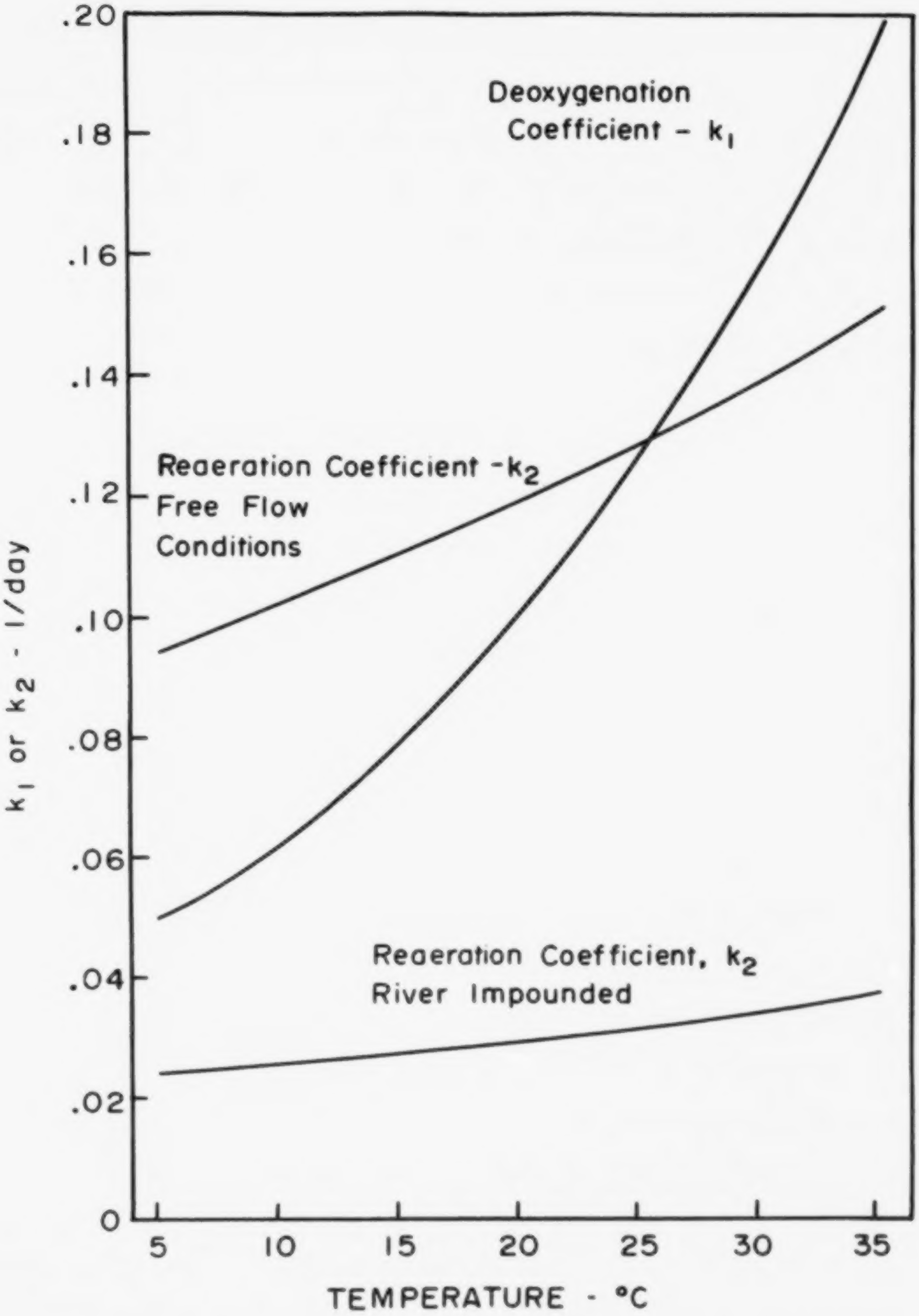


FIGURE IV - 8 SELF-PURIFICATION AS A FUNCTION OF TEMPERATURE

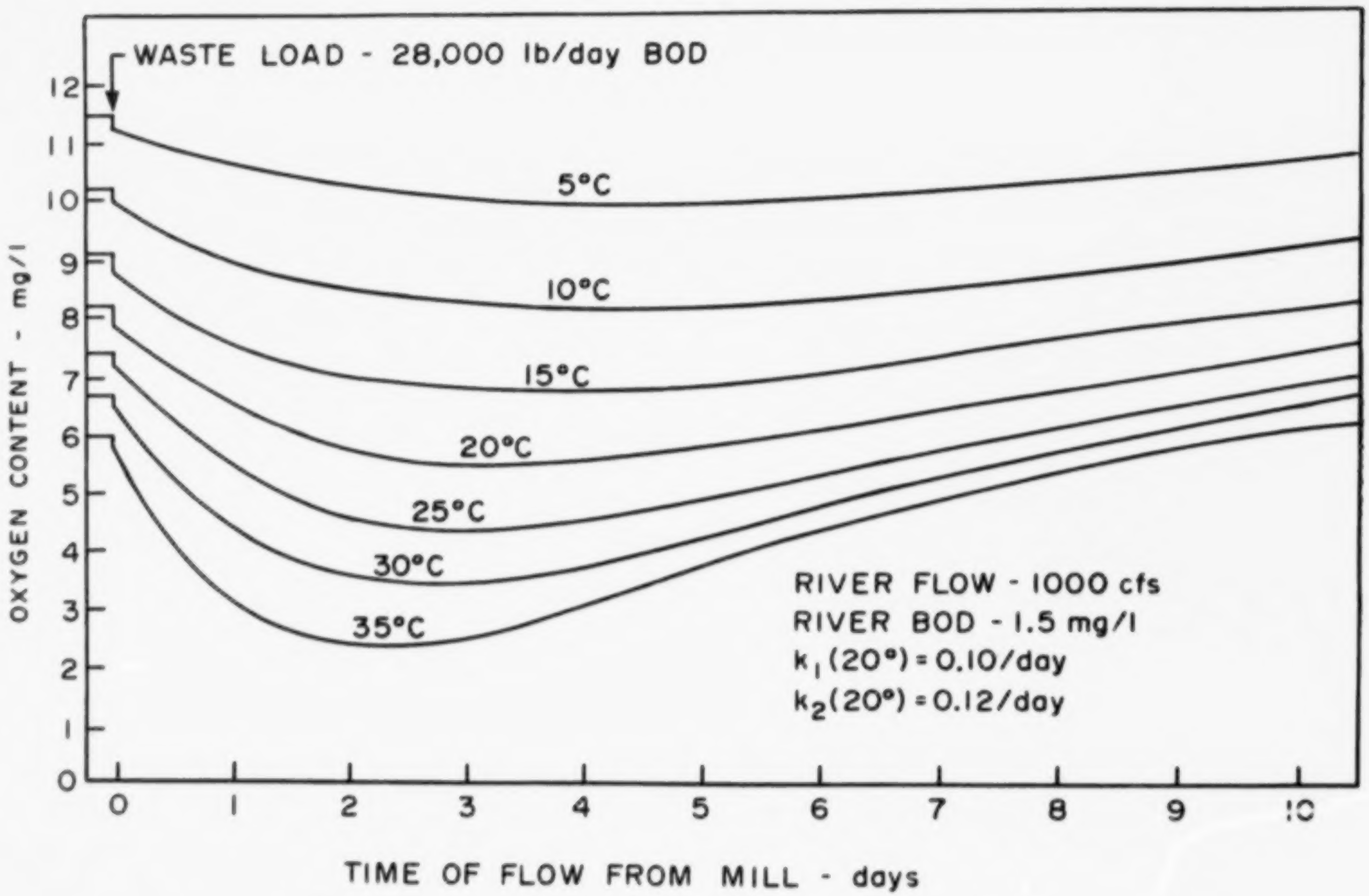


FIGURE IV - 9 OXYGEN-SAG CURVE-FREE FLOWING CONDITION

pounds per day of BOD at the existing river temperature of less than 25°C. Even under the free-flowing conditions, however, a temperature of 30°C would cause the dissolved oxygen level to fall below 4.0 mg/l, the minimum required to satisfy the existing stream standards.

Figure IV-10 is presented to show that, because of the combined effects of the water resources developments and the observed temperature increases, the Coosa River can no longer satisfactorily assimilate the 28,000 pound BOD load, as under the previously existing free-flowing conditions.

The quantitative effect of temperature on the waste assimilative capacity of the Coosa River can be shown on Figure IV-II where the possible waste load that would not deplete the dissolved oxygen content of the river below 4.0 mg/l is plotted versus the river water temperature.

It may be concluded from this figure, that if the river temperature were 25°C, a 5°C increase in temperature under free-flow conditions is equivalent to 11,000 pounds per day of BOD and a 5°C increase in temperature under the existing, impounded conditions is equivalent to 5200 pounds per day of BOD.

Note the significant reduction in assimilative capacity already caused by the impoundment and the observed increase in temperature, as demonstrated by comparing the curve for free-flow conditions and the curve for impounded conditions. It is obvious from these curves, which were computed from observed conditions, that the addition of heat and the impoundment of the Coosa River have had the same end result as if an equivalent amount of sewage or other organic waste material were

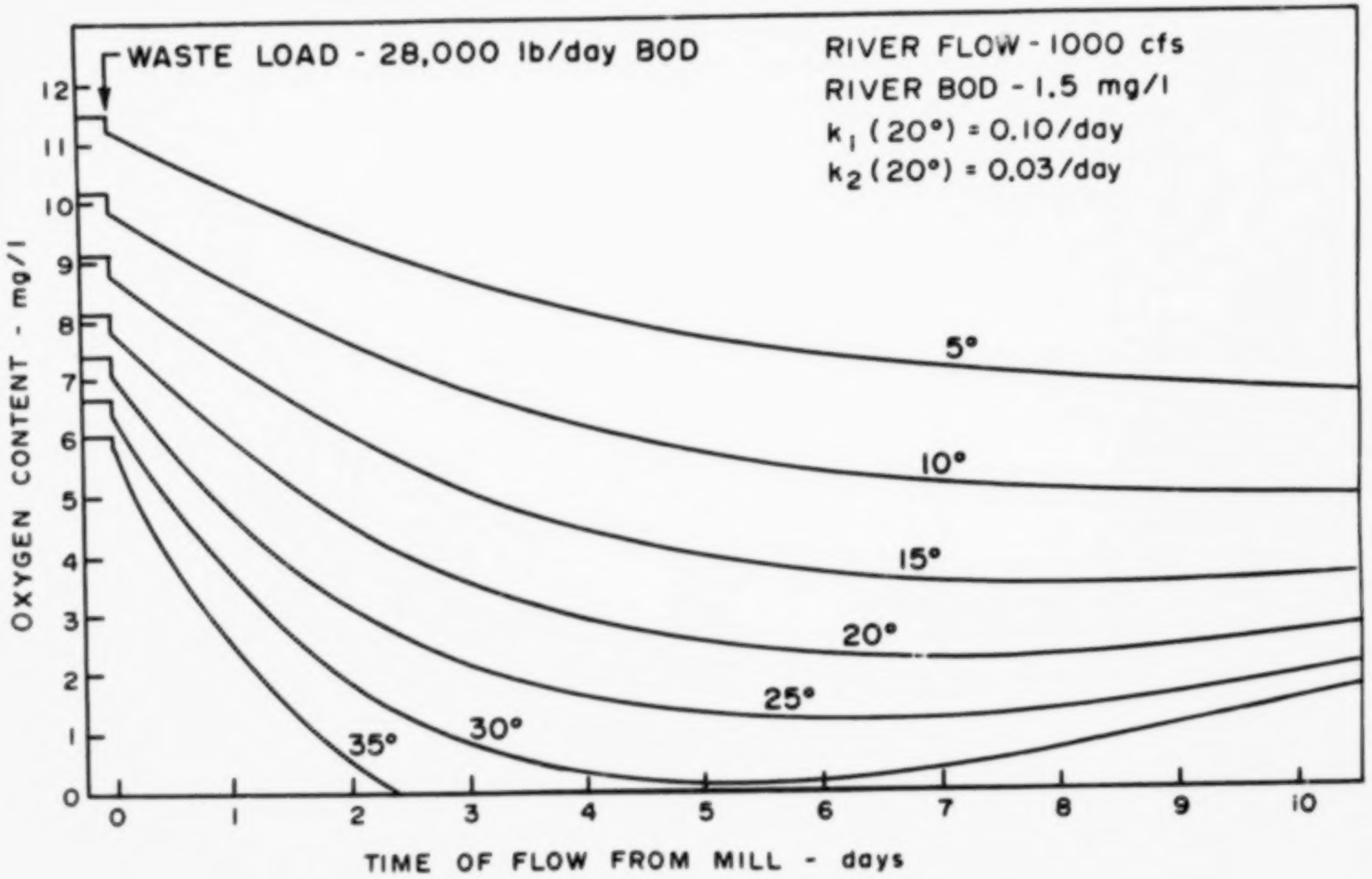


FIGURE IV - 10 OXYGEN-SAG CURVE-RIVER IMPOUNDED

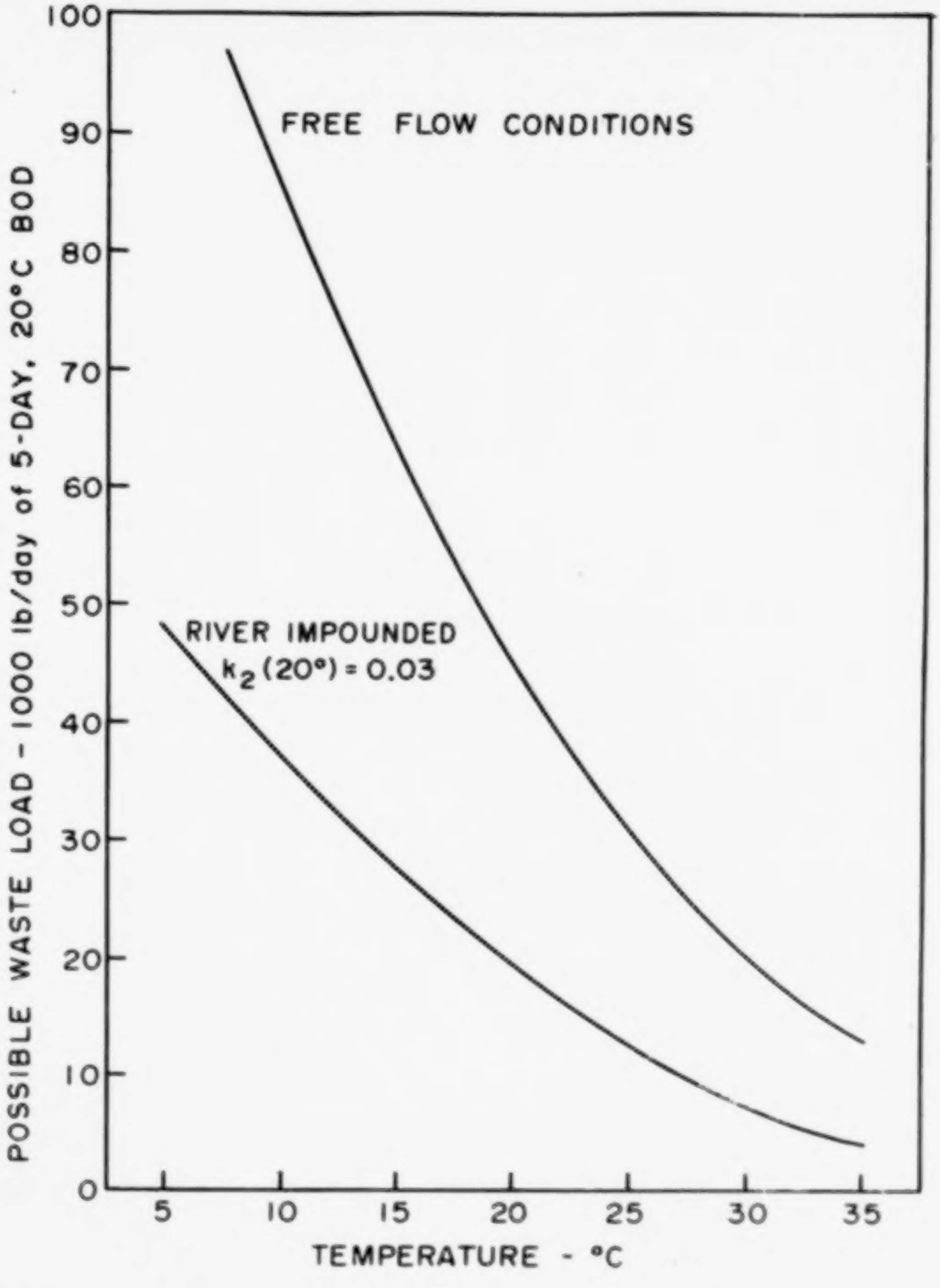


FIGURE IV - 11 PERMISSIBLE WASTE LOAD AT 4 PPM D. O.

added to the river.

Because of the previously described reduction in the waste assimilative capacity of the Coosa River, the mill has reduced its waste load to the river to less than 20,000 pounds of BOD per day which is the allowable load permitted by the Georgia Water Quality Control Board in order to maintain an adequate dissolved oxygen content.

Bohnke (1961, 1966) states that an increase in temperature of the river water of 6°C will cause a 6 percent reduction in self-purification capacity at a minimum oxygen content of 3 mg/l. The loss of assimilative capacity due to a specific power plant on the Lippe was said to be 10,000 population equivalents at low flow.

A recent report by Drummond (1967) estimates that the Chattahoochee River in Georgia can assimilate over three times as much organic material at 20°C as it can at 30°C without excessive depletion of oxygen in the water. The city of Atlanta is quite concerned because of two steam electric generation plants, which, when operating at full load, will raise the maximum average daily river temperature from 20°C to 34°C at minimum flow. It was concluded that, in order to maintain satisfactory dissolved oxygen concentrations in the river during minimum flow, either the steam plant operations must be curtailed or re-regulation of the river must be practiced or cooling towers must be installed.

It may be concluded from these studies that the addition of heated water to a receiving water can be considered equivalent to the addition of sewage or other organic waste material, since both pollutants may cause a reduction in the oxygen resources of the receiving water.

D. Research Needs

Probably the most pressing need for knowledge in reservoir stratification is with respect to reservoir hydrodynamics. Additional information is required on the behavior of inflows and outflows with and without releases from the dam. Changes in temperature distributions caused by hydrodynamic phenomena also need elucidation. Better definition of the stability of stratified flow is required, in particular as it affects the withdrawal of cold water for cooling and the discharge of the warmed water. Obviously, additional information on the behavior of effluents discharging into stratified flow is desirable.

While the overall effects of heated waters on waste assimilative capacity are fairly well known, quantitative definition of changes in waste assimilation with temperature under different hydraulic regimes is needed. For example, if an organic waste is to be discharged into a receiving water also accepting a cooling water discharge, what degree of treatment should be required of the organic waste and how much cooling of the heated water?

The use of colder hypolimnion water for cooling is obviously desirable. However, the hypolimnion may have poor water quality characteristics. This, then raises questions regarding the desirability of artificially overturning a reservoir. While the stratification may produce a poorer quality water, it may be less expensive to treat this water than to lose the advantage of the colder cooling water available to steam electrical generating plants. Obviously, a thorough systems analysis of these alternatives is needed.

Bibliography

American Society of Civil Engineers Committee on Sedimentation, 1963, "Sediment Transportation Mechanics: Density Currents". Journal of the Hydraulics Division, American Society of Civil Engineers, 89, HY5, 77-87.

Anonymous, 1938, "Report on Investigation of Density Currents". Multilith Report U. S. Bureau of Standards.

Bohnke, N., (1966), "New Method of Calculation for Ascertaining the Oxygen Conditions in Waterways and the Influence of the Forces of Natural Purification". Proceedings of the Third International Conference on Water Pollution Research, Munich, Pergamon Press.

Bohnke, N., (1961), "Effect of Organic Wastewater and Cooling Water on Self-Purification of Waters". Proceedings of the 22nd Purdue Industrial Waste Conference.

Drummond, C. E., Jr., (1967), "Water Pollution Control for the Chattahoochee River". Paper presented at Georgia Water Pollution Control Association Conference, Atlanta.

Elder, R. A., 1964, "The Causes and Persistance of Density Currents". Proceedings 3rd Annual Sanitary and Water Resources Engineering Conference, Vanderbilt University, Nashville, Tennessee.

Elder, R. A., Dougherty, G. V., June 1956, "Thermal Density Underflow Diversion Works for Kingston Steam Plant". Preprint, American Society of Civil Engineers Conference, Knoxville, Tennessee.

Jones, S. Leary; 1964, Personal Communication.

Krenkel, P. A., Parker, F. L., and Thackston, E. L., 1969, "Impoundment and Temperature Effect on Waste Assimilation". Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Volume 95, No. SA1.

Krenkel, P. A., 1967, Report to World Health Organization on Poland 0026 Project; 1 September, Copenhagen, Denmark.

Krenkel, P. A., Cawley, W. A. and Minch, V. A., 1965, "The Effects of Impoundments on River Waste Assimilative Capacity." Journal Water Pollution Control Federation, 37, 9.

Kittrell, F. W., 1959, "Effects of Impoundments on Dissolved Oxygen Resources." Sewage and Industrial Wastes Journal, 31, 1065.

Muskie, E., (1967), "Thermal Pollution: Senator Muskie Tells AEC To Cool It." Science, 158.

CHAPTER V-1

BENEFICIAL EFFECTS OF HEAT ADDITIONS

Though the predominant results of heating up our natural water are detrimental to the propagation of game fish and reduce the assimilative capacity of a stream, there are some beneficial effects due to the warmed waters. The total amount of waste heat produced per year, however, is so great that even if all the suggestions for use of waste heat for beneficial use were adopted, the excess heat remaining would still be a problem. For example, the waste heat from power generation would be more than sufficient to heat every home in America. In the following sections are listed the existing and proposed beneficial uses.

A. District Heating:

Possibly the most advanced use of waste heat is for district heating (Santala, 1966). This has been used in Finland for the 20,000 inhabitant city of Tapiola Garden since 1953. The English also have used waste heat for district heating.

B. Increased Biological Production:

Though it has been observed that on the Potomac River and many other rivers that fishermen tend to congregate in the winter in the heated pools below power stations for better fishing, it has also been noted that fishing is poorer in the summer (Elser, 1965).

Research into the possible increased growth of fish below steam electric generating plants has been underway at least since 1953. However, definitive statements are still not possible. In 1953, the Central

Electricity Generating Board determined the rate of growth of flounder at the Newton Abbot Generating Station (Iles, 1963a). Some of the earlier work had dealt with the possibility of utilizing increased yields of algae for food material and talked of farms below the sea (Raymont, 1957). In 1962 the experiments were extended to feed the algae to clams to help solve the problems of harvesting the algae and to ease the preparation of the final product (Ansell, 1962). The economics of the production have not been completed.

Mihursky has suggested a variety of possible constructive uses of thermal additions to estuaries, including a complete recycling of organic wastes from humans to sewage treatment plants to inorganic fertilizers to algae, zooplankton, shellfish and fish to food processing to people to organic wastes, etc. Utilization of the waste heat could be made at the sewage treatment plant, in the enhanced growth of algae, zooplankton, shellfish and fish, and district heating (Mihursky, 1967). Studies of individual sections of this cycle are being carried out.

At Turkey Point, shrimp farming in the effluent of the Turkey Point Power Plant is being studied: Pompano cultivation will also be studied there (Anon, 1968a). Lobsters may also benefit from heated waters. It has been suggested that the lower yields of lobster in recent years may be due to cooler waters in their breeding grounds off the Maine Coast. It has been further suggested that the heated discharge from cooling stations could be used to warm shoreline coves to increase lobster yields (Anon, 1968b).

Long Island Lighting Company at Northport, New York is experimenting with the aquaculture of oysters in the heated discharge from their nuclear power plant (Kovaly, 1968). A report from the Electric Boat Division has suggested that it might be possible to raise 18 million kilograms of warm water fishes annually by using thermal discharges. Present annual per capita consumption of fish is approximately 10.5 pounds (Lerner, 1968).

Perhaps the most original suggestion is that heated waters in England be used to raise ornamental fish, some of which sell for over $140 per pound (Iles, 1963a). In addition, Chinese Carp, Tilapia, Gross Carp, Silver Carp, and Rainbow and Brown Trout have been used in fish culture experiments by England's Central Electricity Generating Board (Iles, 1963b).

Some inadvertant beneficial use of the warmed waters may have already occurred. The growth and spread of the American Hard-shell Clam in English waters may well have been due to the warming effect of cooling water effluents (Ansell, 1963).

The ability of thermophilic algae to survive at temperatures as high as 85 deg. C. has been reported. Recent studies, however, indicate that cyanidium will not undergo cell division at temperatures much greater than 60 deg. C. (Ascione, Southwick, and Fresco, 1966). It is possible, therefore, for some species to survive very high temperatures. At Yellowstone Park the optimal temperature for algae development in the alkaline hot springs was 51 deg. to 56 deg. C. (Brock and Brock, 1966).

C. Control of Marine Fouling

The reversal of the flow of cooling sea water streams through the intake pipes in order to raise the temperature to limit the creatures inhabiting the pipes is not new. The use of heated waters for the control of mussels for a station on the coast of California is shown to be less expensive than the use of chlorine (Chadwick, Clark, Fox, 1950). A follow-up of the original work 10 years later shows that thermal control was still the most successful as well as the most practical means of control fouling (Fox and Corcoran, 1958).

D. Water Works Treatment:

Many studies have been made on the effect of temperature on water treatment processes (Burnson, 1938; Camp, Root,Bhoota, 1940; Renn, 1957; Velz, 1934). Renn sums up the experience to that time (1956) by noting that Fair and Geyer (1954) find that "the efficiency and effectiveness of flocculation and of filtration of floc-bearing water rises with rising temperatures". Most other authors agree though Velz (1934) disagreed. Camp's studies (Camp, Root, Bhoota, 1940) showed that the optimum condition for flocculation is determined by 3 variables, iron-alum dose, pH, and temperature. Velz's findings may be in agreement with this since he also showed that isoelectric point of the flocculating system shifts drastically with temperature. Because of this increased efficiency in flocculation the State of Pennsylvania's Committee on the Effects of Heated Discharges found in 1962 that savings in chemicals for water treatment would be 30 to 50 cents per million gallons for each 10 deg. F. rise in temperature (Arnold, 1962). This may be compared with an average cost of chemicals of $14 for treating water and a range of $3 to $30 per million gallons.

E. Waste Treatment

There is a considerable body of literature on the effects of heating sludge, but little information on the effects of temperature greater than 60 deg. C. Recently, raw sewage has been heated to 100 deg. C. to determine if there were any improvements in settling efficiency.

Crotty, et al. (Crotty, Feng, Skrinde, Kuzminsky, 1968) found that heat treated wastes were more homogenous, and settled faster. Further work is required. Earlier German work cited by Crotty on preheating sewage and raw sludge to 100 - 120 deg. C. shows that they will be more amenable to sedimentation and biological treatments.

F. Irrigation:

The intake of the Oroville Power Plant on the Feather River was especially constructed at considerable extra expense to draw water from various levels to avoid damage to downstream agricultural interests by excessively cool water (Raney, 1963). The same results could have been achieved by mixing the heated waters from a thermal power station with the discharge from the hypolimnion of a storage reservoir.

G. Ice-Free Shipping Lanes:

A recent study by Dingman, et al., (1968) has shown that it should be possible to keep significant portions of the Saint Lawrence Seaway open the year around by the judicious location of central station electric power complexes. This would save transportation costs of several million dollars per year. It is estimated that a 600 mw_e reactor could keep a stretch of the river between 11 and 16 miles ice-free. No study was made of the ecological effect of such an undertaking, however.

H. Water and Sediment Discharge:

Since the viscosity and density of water decreases with temperature, a change in temperature should have an effect on both sediment transport and water flow. It had previously been thought that the variation of only a few degrees would have a small effect (Burke, 1966). More recent data, however, suggests that these effects may be quite important (Burke, 1969). Colder water is more viscous than warmer water and therefore has a higher carrying capacity for sediment than does warmer water. In warmer water, coarser material settles out and so for any crossing in the river (which acts as a submerged weir) there is less flow past that cross-section for the same stage. Decreasing water temperature may be assumed to make a difference of 10 to 20 percent in expected discharge for a given stage (Burke, 1969). Sudden rises in temperature may cause such a deposition of coarse material to ground ships following sailing lines.

Studies by Colby and Scott have indicated that changes in temperature affect bed material discharge in complex ways (Colby and Scott, 1965). The thickness of the laminar sublayer is changed with the temperature, but it is usually only a small effect. The vertical distribution of suspended material is greatly affected by temperature changes and indicates an approximate doubling of bed material discharge when temperatures drop from 80°F to 40°F, assuming that the mean velocities, depths, and sizes of bed sediments remain constant. Finally, the bed configuration and therefore the resistance to flow are effected by changes in temperature. Their effect may be large or small. Colby in an earlier summary of fluvial sediments (Colby, 1963) had noted that the fall velocities of sediment particles increase with an increase in water temperature. For particles larger than 1 mm., however, the percentage increase is small. For sediments in the size range 0.1 to 0.4 mm., fall velocity, vertical distribution and discharge of sediments is greatly affected by temperature changes (Colby, 1963). Franco (1968) in a more recent study confirms some of these results and finds that the effects of water temperature on bed load appear to be mostly in the formation of the bed and bed roughness.

I. Water Supply Source

A serendipitous benefit was obtained in Henderson, Kentucky, when it was found necessary to replace the town's water supply system. Over one quarter of a million dollars was saved by the use of the condenser cooling waters as the intake to the tower's water supply system (Highland, 1962). Fortunately, no chemicals were added to the intake water and the warmer water had not to that date caused any problems.

J. Research Required

Though it has already been pointed out that it is highly unlikely to find beneficial uses for all the heat that would ordinarily be wasted to the atmosphere or hydrosphere, there are some uses as already indicated which could reduce the negative effects of present day discharges.

Though some of the possibilities described below may not be economical if one does not take into account the social and dispersed costs of thermal pollution, they may very well be economical if the user is credited for the social costs avoided by these usages.

1. Urban applications

While some European communities are specifically designed to use the steam from the condenser for heating and some American cities, Boston for example, do use steam from the public utilities for heating, the systems are not designed for air conditioning as well. Therefore, the waste heat load is dumped into the streams during the summer, the most critical portion of the year. It would be useful to see if one could economically design large scale air conditioning systems using the small differences in temperature between the waste heat and the atmosphere.

The use of cooled water systems for air cooling is becoming more widespread and this methodology should also be investigated for large scale city use.

In northern cities, the waste heat might be used to maintain streets and sidewalks ice and snow free during the winter and to provide heated malls in downtown areas.

2. Industrial, Urban-Industrial and Agro-Industrial Complexes

An analysis of the costs of heating, drying and hot water for industry may show that the use of low-grade heat may be more efficient if social costs are taken into account.

The joint use of energy by combination of the urban, industrial, and agricultural demands may make economical the use of the low energy heat whereas it may not be economical if utilized singly.

Energy may be used to produce power and fertilizer and then it may be possible to use the low grade heat to desalinate brackish waters and brine, to supply process heat to industry and to induce micro-climates conducive to increased agricultural production.

3. Agriculture

With a world-wide shortage of food, it may be worthwhile to determine the extent to which the growing season could be extended by the use of heated irrigated waters and the creation of a warmer microclimate for an agricultural region. The type of crops raised may also be changed by the change in temperature. Though some of this information is available to the agriculturists it should be put in a form suitable for the use of energy and pollution specialists and brought to their attention.

4. Aquaculture

Though some work is already underway to determine if increased yields of seafoods could be raised by utilizing heated waters, the effort is not substantial enough. The effect of the higher temperatures on the health of the organisms and the quality of their meat has not yet been tested. To date, only high value seafoods; lobster, oysters, shrimps, and pompano for example, have been studied. If many of the major oceanic fisheries are already being utilized to capacity, then even larger scale use of heated waters to raise commercial fish may be warranted and should be investigated.

5. Ice Free Ports

Though it has been calculated that it would be possible to keep significant portions of the St. Lawrence Seaway ice free, detailed calculations for requirements on other important waterways have not yet been made.

No study has been made of the ecologic effects of such an undertaking. The determination of the ecologic effects would be necessary prior to the authorization of such projects.

BIBLIOGRAPHY

Anonymous, 1968a, "Thermal Effluent May Cut Cost of Shrimp Cocktail". *Electrical World*, 30.

Anonymous, 1968b, "Lobsters, Warmed and Simulated". *Science News*, *93*, 169.

Ansell, Alan D., 1962, "An Approach to Sea Farming". *The New Scientist*, *14*, 3657-3667.

Ansell, Alan D., 1963, "*Venus Mercenaria* (L) in Southampton Water". *Ecology*, *44*, 397.

Arnold, G. E., 1962, "Thermal Pollution of Surface Supplies". *Journal of American Water Works Association*, *54*, 1336.

Ascione, R., Southwick, W., and Fresco,J. R., 1966, "Laboratory Culturing of a Thermophilic Algae at High Temperature." *Science*, *153*, 754.

Brock, T. D., and Brock, M. L., 1966, "Temperature Optima for Algal Development in Yellowstone and Iceland Hot Springs." *Nature*, *209*, 734.

Burke, P. P., 1966, "Effect of Water Temperature on Discharge and Bed Configuration - Mississippi River at Red River Landing, Louisiana". Corps of Engineers, Vicksburg, Miss., 3.

Burke, P. P., 1969, "Water Temperature and Discharge". American Society of Civil Engineers preprint, 12, Red River Landing, Louisiana.

Burnson, B., 1938, "Seasonal Temperature Variations in Relation to Water Treatment". *Journal of American Water Works Association*, *30*, 793.

Camp, T. R., Root, D. A., and Bhoota, B. V., 1940, "Effects of Temperature on Rate Floc Formation". *Journal of American Water Works Association*, *32*, 1913.

Chadwick, W. L., Clark. F. S., and Fox, D. L., 1950, "Thermal Control of Marine Fouling at Redondo Steam Station of the Southern California Edison Company". *American Society of Mechanical Engineers - Transactions*, *72*, 131.

Colby, B. R., 1963, "Fluvial Sediments". U. S. Geological Survey Bulletin #1181-A, U. S. Government Printing Office, Washington, D.C.

Colby, B. R., and Scott, C. H., 1965, "Effects of Water Temperature on the Discharge of Bed Material". Geological Survey Professional Paper 462-G, United States Government Printing Office, Washington, D. C., G-I.

Crotty, P., Feng, T., Skrinde, R., and Kuzminski, L., 1968, "The Use of Heat to Improve Water Treatment". Presented at the First Annual Northeastern Regional Anti-Pollution Conference, University of Rhode Island, 23.

Dingman, S. L., Weeks, W. F., and Yen, Y. C., 1968, "The Effects of Thermal Pollution on River Ice Conditions". Water Resources Research, 4.

Elser, H. J., 1965, "Effects of a Warmed-Water Discharge on Angling in the Potomac River, Maryland, 1961-1962". Prog. Fish. Cult., 27, 85.

Fair, G. M., and Geyer, J. C., 1954, "Water Supply and Wastewater Disposal". John Wiley and Sons, New York, N. Y.

Fox, D. L., and Corcoran, E. F., 1958, "Thermal and Osmotic Countermeasures Against Some Typical Marine Fouling Organisms". Corrosion, 14, 131.

Fresco, John J., 1968, "Effects of Water Temperature on Bed-Load Movement". Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, 343-352.

Highland, J. T., 1962, "Power-Plant Cooling Water Provides Domestic Supply". Public Works, N. Y., 93, 101-104.

Iles, R. B., 1963a, "Cultivating Fish for Food and Sport in Power Station Water". New Scientist, 117, 227-229.

Iles, R. B., 1963b, "The Subtropical Waters of Britain". Journal of the Institution of Electrical Engineers, 9, 245-246.

Kovaly, Kenneth H., 1968, "Heat Pollution - or Enrichment". Industrial Research, 31.

Lerner, W., 1968, "Statistical Abstract of the United Stated, 1968". U. S. Government Printing Office, Washington, D. C.

Mihursky, J. A., 1967, "On Possible Constructive Uses of Thermal Additions to Estuaries." Bio-Science, 17, 698-702.

Raney, F., 1963, "Rice Water Temperature". Rice Journal, Dec., 19-22.

Raymont, J. E. G., July 18, 1957, "Sea Plants for Food". The New Scientist, 10-11.

Renn, Charles E., 1957, "Warm-Water Effects on Municipal Supplies". Journal of American Water Works Association, 49, 410.

Santala, Veikko, 1966, "How District Heating Serves Finnish City of 20,000". Heating, Piping, and Air Conditioning, 38, 129-135.

Velz, C. J., 1934, "Influence of Temperatures on Coagulation. Civil Engineering, 4, 345.

CHAPTER VI - 1

PREDICTION OF HEAT DISSIPATION

Obviously, the simplest method of disposing of waste heat is to discharge it directly to the receiving water and then allow natural forces to bring the water back to an equilibrium temperature. This process is known as once through cooling and is shown schematically on Figure VI-1. In order to predict the behavior of these heated effluents, it is necessary to resort to an energy balance.

Much of the work on the heat balance has been a result of the interest in evaporation losses demonstrated by hydrologists and hydraulic engineers and is therefore primarily concerned with the prediction of evaporation rates. A brief presentation of these studies will be made. For a more extensive literature review of this subject, the reader is referred to Anderson (1960), U. S. Geological Survey (1954), U. S. Public Health Service (1963) and Edinger and Geyer (1965).

A. The Energy Balance

The use of the energy balance approach for estimating evaporation, elucidated by Angstrom (1920), was used by Schmidt (1915) to approximate ocean evaporation and has since been applied to compute evaporation from water bodies of all sizes. The relatively recent development of more sophisticated instrumentation has allowed the energy budget to be utilized with a fair degree of reliance, if conditions are appropriate.

The energy budget was first tested against a water budget control at Lake Hefner in 1950-51 (Anderson, 1954). It was concluded that

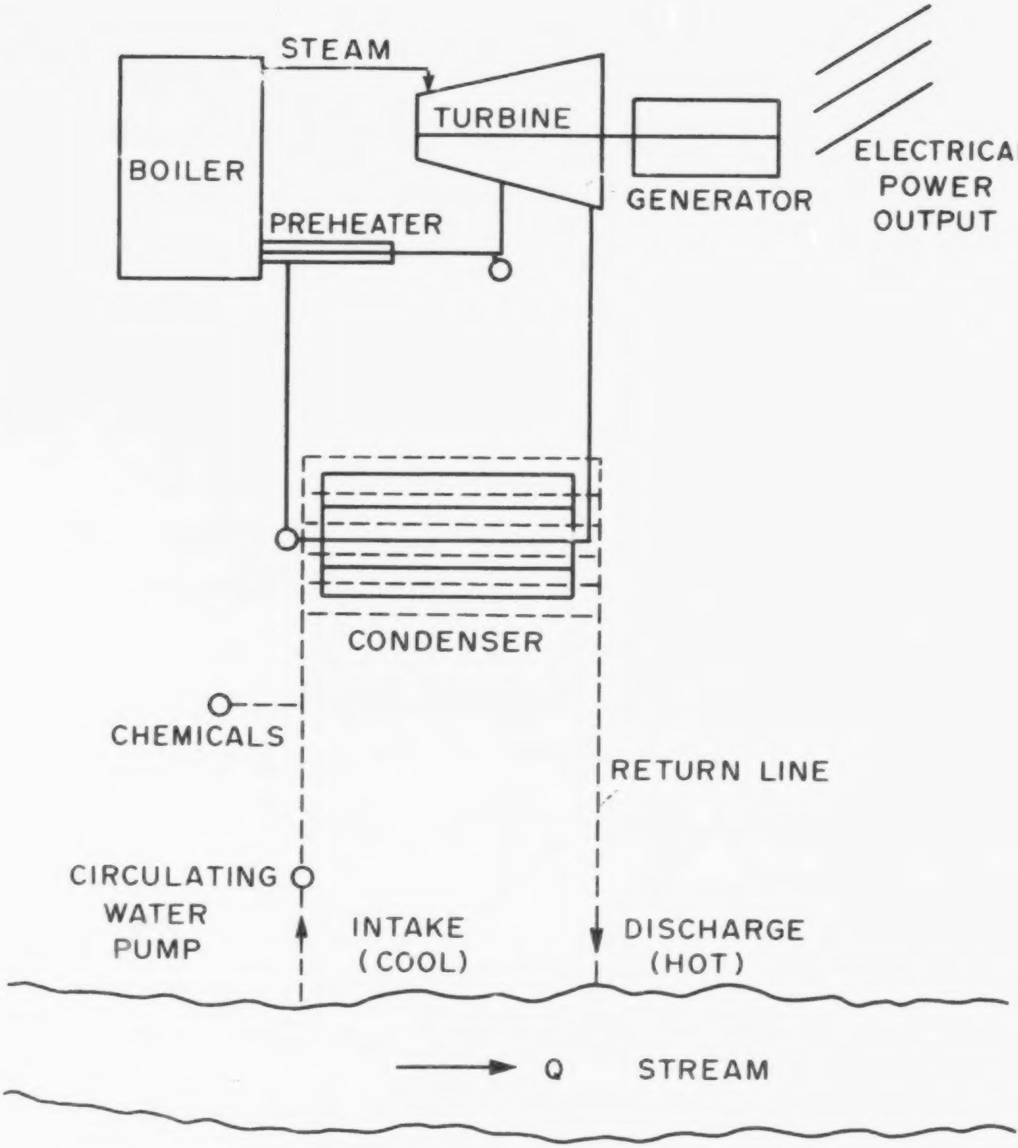

STEAM
BOILER
TURBINE
GENERATOR
ELECTRICAL
POWER
OUTPUT
PREHEATER
CONDENSER
CHEMICALS
RETURN LINE
CIRCULATING
WATER
PUMP
INTAKE
(COOL)
DISCHARGE
(HOT)
Q
STREAM

FIGURE VI - 1 RUN OF THE RIVER ELECTRICITY GENERATING STATION COOLING SYSTEM

satisfactory results were obtained for periods of ten days or more. A second check against a water budget was made at Lake Colorado City, Texas in 1954-55, where inflow was extremely small and outflow was zero (Harbeck, 1959). The components of the energy budget per unit surface area of a reservoir per unit time may be written as follows (World Meteorological Organization, 1966):

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q \qquad \text{VI-1}$$

where:

Q_s = short-wave radiation incident to the water surface;

Q_r = reflected short-wave radiation;

Q_a = incoming long-wave radiation from the atmosphere;

Q_{ar} = reflected long-wave radiation;

Q_{bs} = long-wave radiation emitted by the body of water;

Q_v = net energy brought into the body of water in inflow, including precipitation, and accounting for outflow;

Q_e = energy utilized by evaporation;

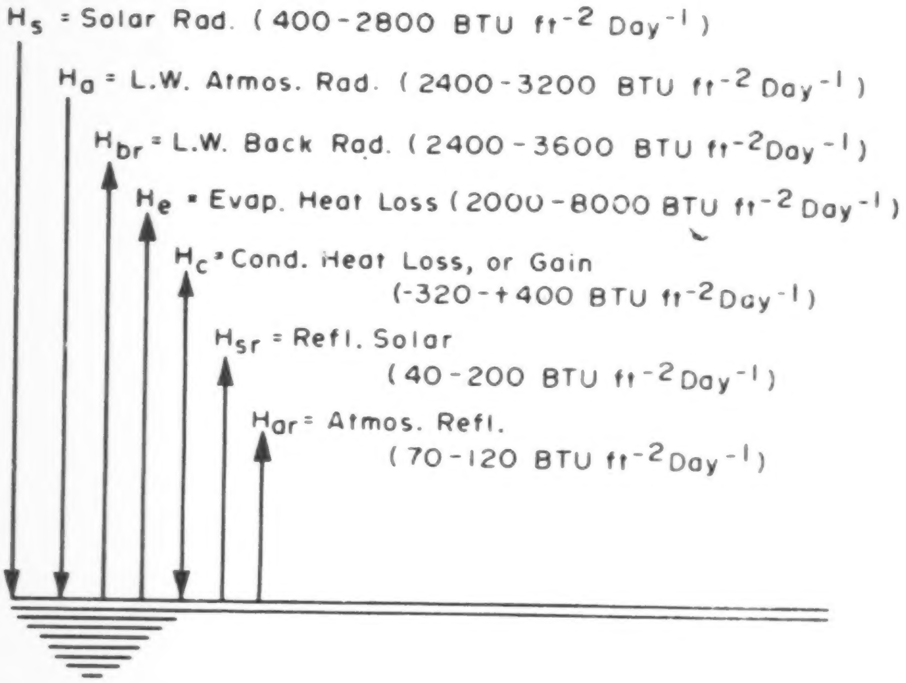
Q_h = energy conducted from the body of water as sensible heat;

Q_w = energy carried away by the evaporated water;

Q = increase in energy stored in the body of water.

Edinger and Geyer (1965) have depicted the heat transfer terms across a water surface as shown on Figure VI-2, noting temperature dependent terms and typical values. The addition of heated water discharges simply superimposes the heat addition upon the natural dissipations and additions of energy.

Figure VI-3 shows the results of calculations by Bergstrom (1968) for a water surface in central Illinois. The data demonstrate the


H_s = Solar Rad. (400-2800 BTU ft^{-2} Day^{-1})
H_a = L.W. Atmos. Rad. (2400-3200 BTU ft^{-2} Day^{-1})
H_{br} = L.W. Back Rad. (2400-3600 BTU ft^{-2} Day^{-1})
H_e = Evap. Heat Loss (2000-8000 BTU ft^{-2} Day^{-1})
H_c = Cond. Heat Loss, or Gain (-320-+400 BTU ft^{-2} Day^{-1})
H_{sr} = Refl. Solar (40-200 BTU ft^{-2} Day^{-1})
H_{ar} = Atmos. Refl. (70-120 BTU ft^{-2} Day^{-1})

NET RATE AT WHICH HEAT CROSSES WATER SURFACE

$$\Delta H = (H_s + H_a - H_{sr} - H_{ar}) - (H_{br} \pm H_c + H_e) \text{ BTU ft}^{-2}\text{ Day}^{-1}$$

H_R

Absorbed Radiation
Independent of Temp.

Temp. Dependent Terms

$H_{br} \sim (T_s + 460)^4$

$H_c \sim (T_s - T_a)$

$H_e \sim W(e_s - e_a)$

FIGURE VI - 2 MECHANISMS OF HEAT TRANSFER ACROSS A WATER SURFACE

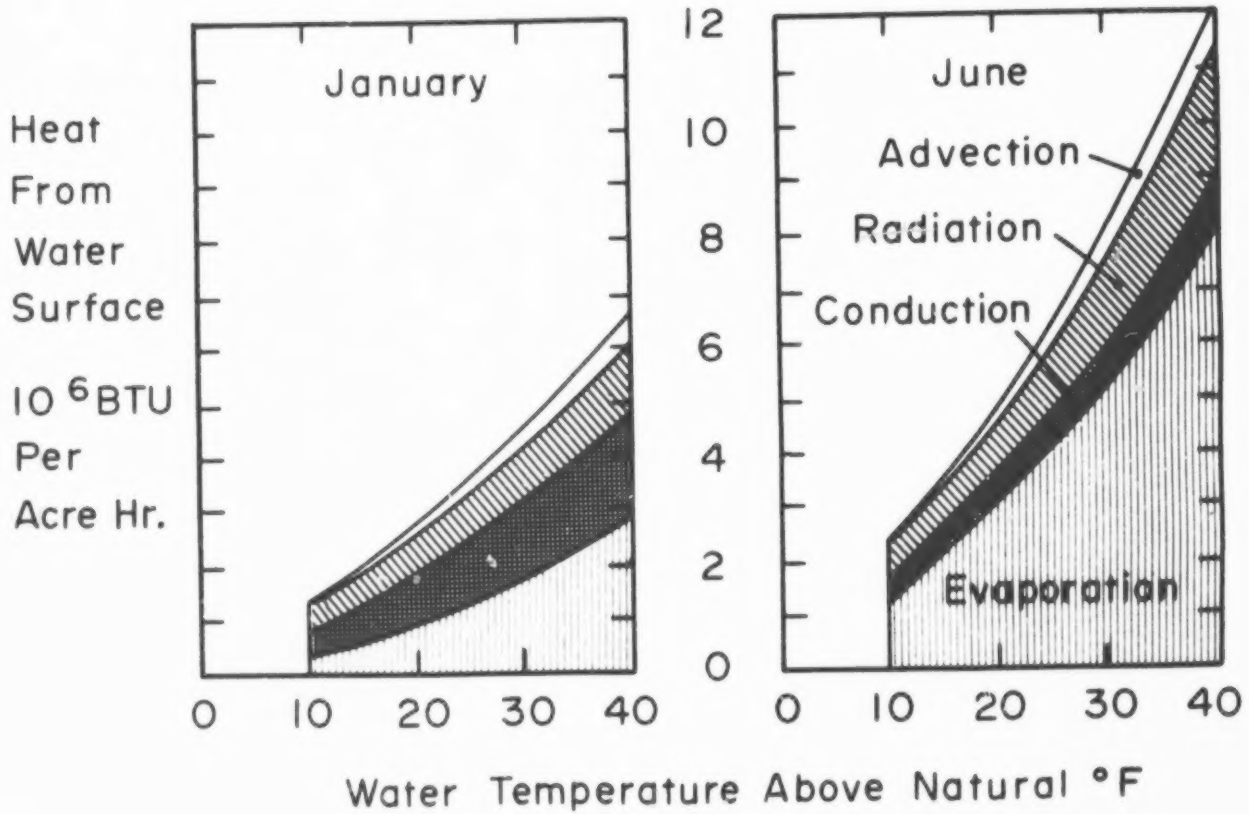


FIGURE VI - 3 HEAT DISSIPATION FROM WATER SURFACE BY EVAPORATION, RADIATION, CONDUCTION, AND ADVECTION DURING JANUARY AND JUNE

relationship of rate of heat dissipation to elevation of the water surface temperature over natural temperature and the mechanisms by which this dissipation is achieved. It is significant to note that the rate of heat dissipation for a given rise in temperature is greater in summer than in winter and also that the heat dissipation by evaporation is much greater in summer than in winter. These calculations would appear to support the contention that heated effluents should be discharged in the most concentrated form possible (neglecting any biological or other effects) in order to dissipate the heat most rapidly.

While the terms in the energy budget are discussed in detail by Anderson (1954) and Edinger and Geyer (1965), brief comments pertaining to their determination are in order.

Short Wave Radiation, Q_s:

Short wave radiation originates directly from the sun, although the energy is depleted by absorption by ozone, scattering by dry air, absorption scattering by particulates and absorption and scattering by water vapor. It varies with latitude, time of day, season and cloud cover. Thus, while this quantity can be empirically calculated, it is much better to measure it using a Pyrheliometer which will give the accuracy required for the energy budget.

Long Wave Atmospheric Radiation, Q_a:

Long wave atmospheric radiation depends primarily on air temperature and humidity and increases as the air moisture content increases. It may be a major input on warm cloudy days when direct solar radiation approaches zero. It is actually a function of many variables, including carbon dioxide and ozone, although it can be fairly accurately calculated by means of empirical formulation as demonstrated in the Hefner studies. It can be measured with the Gier-Dunkle Flat Plate Radiometer, although it is more convenient to calculate than measure.

Reflected Short Wave and Long Wave Radiation, Q_r and Q_{ar}:

Solar reflectivity, (R_{sr}), is more variable than atmospheric reflectivity, (R_{ar}), inasmuch as the solar reflectivity is a function of sun altitude and cloud cover, while atmospheric reflectivity is relatively constant. The Lake Hefner studies demonstrated the atmospheric reflectivity to be approximately 0.03, while on an annual basis, the solar reflectivity was 0.06. The Hefner studies used the equation:

$$R_{sr} = a\,S_a^{\;b} \qquad \text{VI-2}$$

to determine solar reflectivity, where S_a is the sun altitude in degrees and a and b are constants depending on cloud cover. Note that $R_{sr} = Q_r/Q_s$ and $R_{ar} = Q_{ar}/Q_a$.

Long Wave or Back Radiation, Q_{bs}:

Water sends energy back to the atmosphere in the form of long wave radiation and radiates almost as a perfect black body. Thus, the Stefan-Boltzman fourth power radiation law can be utilized, or:

$$Q_{bs} = 0.97\sigma\,(T_o + 273)^4 \qquad \text{VI-3}$$

where:

0.97 = Emissivity of water

Q_{bs} = long wave radiation in calories/cm^2/day

σ = Stefan-Boltzman constant = 1.171×10^{-7} calories/cm^2/deg^4/day

T_o = Water surface temperature in °Centigrade.

All that is required to compute Q_{bs} is the water surface temperature and a table giving the value of Q_{bs} for any temperature, T_o, is readily available or computable.

Energy Utilized by Evaporation, Q_e:

Each pound of water evaporated carries its latent heat of vaporization of 1055 BTU's at 68°F, thus Q_e is a significant term in the energy budget. The Lake Hefner study was explicitly promulgated for determining correct evaporation relationships and resulted in the following equation:

$$Q_e = 11.4W\ (e_s - e_a) = BTU/ft^2/day$$

which is of the general type of evaporation formula:

$$E = (a + bW_x)\ (e_s - e_a) \qquad \text{VI-5}$$

where:

a, b = empirical coefficients

W_x = wind speed in mph at some elevation, x ft. above water

e_a = air vapor pressure, mm-Hg.

e_s = saturation vapor pressure of water determined from water surface temperature, mm-Hg.

E = evaporation = $Q_e/\rho L$ ft/day

ρ = density of evaporated water lbs/ft^3

L = latent heat of vaporization BTU/lb

Many expressions have been developed for estimating the evaporation rate, the coefficients differing because of variation in the reference height for measurement of wind speed and vapor pressure, the time period over which measurements are averaged and local topography and conditions. As stated by Edinger and Geyer (1965), "It would also be expected that the coefficients would be much different for rivers and streams than for lakes and might well be dependent on water velocity and turbulence, particularly in the case of smaller rivers".

Energy Conducted As Sensible Heat, Q_h:

Heat enters or leaves water by conduction if the air temperature is greater or less than water temperature. The rate of this conductive heat transfer is equal to the product of a heat transfer coefficient and the temperature differential.

A single direct measurement of this quantity is not available and recourse to an indirect method is necessary. The method involves using average figures of air temperature, water surface temperature and humidity for the period in question and computing the ratio of Q_h to Q_e, which is known as the Bowen Ratio and expressed as:

$$R_B = \frac{Q_h}{Q_e} = \frac{0.61\ P\ (T_o - T_a)}{1000\ (e_o - e_a)} \qquad \text{VI-6}$$

where:

P = atmospheric pressure in millibars

T_a = temperature of air in °C

T_o = temperature of water surface in °C

e_o = saturation vapor pressure corresponding to temperature of water surface in millibars

e_a = vapor pressure of air at height at which T_a is measured in millibars

Energy Carried Away by Evaporated Water, Q_w:

Water being evaporated from the surface is at a higher temperature than the lake water, and thus energy is being removed. Though some believe this term is included in the conductive energy term, it is relatively small and can be readily computed from:

$$Q_w = \rho_e \, c \, E \, (T_e - T_b) = \frac{\text{cal}}{\text{cm}^2\text{-day}} \qquad \text{VI-7}$$

where:

ρ_e = density of evaporated water, gm/cm^3

c = specific heat of water, cal/gm

E = volume of evaporated water, gm/cm^2/day

T_e = temperature of evaporated water, °C

T_b = base or reference temperature, °C

Advected Energy, Q_v:

The net energy contained in water entering and leaving the lake may be computed from the following expression:

$$\begin{aligned} Q_v = {} & c_{si} \, V_{si} \, \rho_{si} \, (T_{si} - T_b) + c_{gi} \, V_{gi} \, \rho_{gi} \, (T_{gi} - T_b) \\ & - c_{so} \, V_{so} \, \rho_{so} \, (T_{so} - T_b) - c_{go} \, V_{go} \, \rho_{go} \, (T_{go} - T_b) \\ & + c_p \, V_p \, \rho_p \, (T_p - T_b) \quad \div A \end{aligned} \qquad \text{VI-8}$$

in which:

Q_v = advected energy in cal cm^{-2} day^{-1}

c = specific heat of water ($\approx$ 1 cal g^{-1} deg^{-1})

V = volume of inflowing or outflowing water in cm^3 day^{-1}

ρ = density of water ($\approx$ 1 cal g^{-1} deg^{-1})

T = temperature of water in °C

A = average surface area of reservoir in cm^2.

The subscripts are as follows:

si = surface inflow

gi = groundwater inflow

so = surface outflow

go = groundwater outflow

p = precipitation

b = base or reference temperature, usually taken as 0°C.

Since some of the terms in equation 8 may not be measurable, a water budget is performed for the same period, evaporation is estimated, and the unknown terms are found by trial and error. It is also possible that groundwater and precipitation terms may be negligible in some cases and therefore ignored.

Increase in Energy Stored, Q:

The change in storage in the energy-budget equation may be either positive or negative, and is found from properly averaged field measurements of temperature and the following equation:

$$Q = c\rho_1 V_1 (T_1 - T_o) - c\rho_2 V_2 (T_2 - T_o) \div \Delta t \qquad \text{VI-9}$$

in which:

Q = increase in energy stored in the body of water in cal cm^{-2} day^{-1}

c = specific heat of water (≈ 1 cal g^{-1})

ρ_1 = density of water at T_1 (≈ 1 g cm^{-3})

V_1 = volume of water in the lake at the beginning of the period in cm^3

T_1 = average temperature of the body of water at the beginning of the period in °C

ρ_2 = density of water at T_2 ($\simeq 1$ g cm^{-3})

V_2 = volume of water in the lake at the end of the period, in cm^3

T_2 = average temperature of the body of water at the end of the period in °C

T_o = base temperature in °C

A = average surface area in cm^2 during the period

t = length of period in days.

From this necessarily brief discussion of the various parameters comprising the energy-balance, it may be concluded that it is possible to predict heat dissipation using these concepts. Obviously, the reliability of the results will depend on the degree of sophistication used in the theoretical approach and the frequency and accuracy of the measurements taken.

B. Heat Dissipation From Reservoirs and Lakes

One of the first attempts to predict the dissipation of heat from cooling ponds was by Lima in 1936. While the theoretical aspects of heat transfer are not presented, several graphs allowing estimates of areas required for cooling were empirically derived. Similar, although more sophisticated formulations were presented by Throne in 1951. The graphs contained in these papers are quite useful in obtaining rough estimates of cooling pond performances.

The United States Geological Survey has been a pioneer in heat balance studies with several classic publications resulting from rather large field scale investigations. Probably the most widely quoted study in the literature is the Lake Hefner investigation (1954), which was a comprehensive attempt to compare various methods for evaporation determination.

Four methods for the determination of evaporation were examined: the water budget, the energy budget, the use of mass transfer theory, and the use of evaporation pans.

In the water budget method, evaporation is determined by measuring inflow, outflow and changes in storage; however, it is not generally useful because evaporation is often small when compared to errors in measuring inflow, outflow, seepage and bank storage. The energy budget method involves precise measurement of energy changes within the body of water and the mass-transfer concept relates factors affecting mass transfer of water vapor to the evaporation process. The use of pans is subject to error because the experimentally determined "pan coefficients" apply only for the conditions under which they were determined. An excellent review of these procedures and a discussion of required instrumentation is contained in a pre-study publication by the U. S. Navy (Anderson, 1960).

Because of unusually favorable conditions, the water budget method yielded results good enough to use as a base for comparing the other more practical procedures for evaporation determination, inasmuch as errors in the water budget did not exceed 5% of the monthly evaporation. Comparison of the water budget with mass transfer theory proved Sutton's (1949) and Sverdrup's (1937-38) equations to be satisfactory for use with available field instruments, although another quasi-empirical equation was developed.

The energy budget method showed that for over seven days, evaporation could be determined within ±5% if all terms in the energy budget are carefully evaluated, particularly changes in energy storage.

All of the data collected during the Lake Hefner studies are contained in an additional report (United States Geological Survey, 1954), which is useful to determine orders of magnitude and observations required for similar studies.

The studies of Lake Hefner were extended to Lake Mead as described in a later report by Harbeck (1962). Both the energy budget and mass transfer methods were utilized with fairly good results. It was found that evaporation could be estimated closely by knowing only water surface temperature, wind speed, air temperature and humidity.

In order to test the validity of the mass transfer and water budget methods in a humid area, Turner (1966) conducted an evaporation study on Lake Michie in North Carolina. He states that the amount of inflow and outflow of the lake, its size, the availability of an accurate stage-area relation, and the amount and variability of net groundwater seepage are the major factors that determine whether or not a lake can be calibrated by using the mass-transfer water-budget method. The method, using the equation used by Harbeck (1962), combines the mass transfer equation:

$$E = Nu\,(e_o - e_a) \qquad \text{VI-10}$$

with the water budget equation:

$$\Delta H_A = E + S \qquad \text{VI-11}$$

to obtain:

$$\Delta H_A = (E + \delta) = Nu\,(e_o - e_a) + \delta \qquad \text{VI-12}$$

where:

E = Evaporation, feet

N = Mass transfer coefficient

u = Wind speed, miles per hour

e_o = Saturation vapor pressure, millibars, corresponding to temperature of air-water interface

e_a = Actual vapor pressure of air, millibars

ΔH_A = Average change in water-surface elevation adjusted for inflow, outflow and rainfall, feet

δ = Net groundwater seepage, feet.

Lakes with large inflows, outflows and seepage rates usually produce large errors in water-budget computations, therefore measurement of evaporation by energy-budget techniques may be substituted for the water budget to develop the mass transfer coefficient, N. Frenkiel (1963) discussed the application of the combined energy budget-mass transfer method and concluded that the measurements required should extend for at least one year in order to maintain reasonable accuracy.

A study of the energy budget in Lake Ontario is described in an article by Rogers and Anderson (1961); however, the data collected were from different periods, thus placing question on the validity of the results. Koberg (1964) describes methods to compute long-wave radiation from the atmosphere and reflected solar radiation from a water surface. The only parameters required are air temperature, air vapor pressure and the ratio of measured solar radiation to clear sky solar radiation

In an attempt to estimate the possible saving in water resulting from the use of lakes or existing reservoirs instead of cooling towers for the dissipation of heat, Harbeck (1953) reached some interesting conclusions. Using data from the Lake Hefner study and a hypothetical lake, he applied the energy budget to the lake with excess heat added and made similar calculations for a cooling tower. He concluded that, for the dissipation of excess heat for the climatic conditions prevailing at the Texas site, substantial savings in water often can be realized by using an existing reservoir or lake rather than cooling towers. Curves are presented showing the rise in temperature in the reservoir caused by the addition of excess heat and a comparison of reservoir evaporation and water used by evaporation. Another study conducted by Harbeck (1959) on a lake used for cooling water purposes showed that the increase in evaporation caused by the power plant discharge, when expressed as a volume, is directly proportional to the amount of heat added and is practically independent of reservoir contents. Evaporation was determined by the energy budget method and checked by a water budget.

The use of the energy budget method to predict temperatures in reservoirs for water quality control purposes is also discussed in papers by Delay and Seaders (1963), Boyer (1963) and Raphael (1962). In each case, conventional measurement of the parameters previously described were subjected to the usual calculation procedures, resulting in predictive models for temperatures in and downstream from the impoundments. A discussion of instrumentation for water temperature studies is presented by Moore (1963) where it was concluded that temperature could be measured with an accuracy of one degree Fahrenheit.

A major problem encountered with respect to the prediction of temperature distributions in stratified reservoirs is the temperature gradient itself (Orlob, 1967, and Orlob and Selna, 1967).

Orlob proposed a mathematical model to simulate energy distribution in reservoirs and streams which appears to be a most significant contribution. The model, which utilizes the digital computer, was tested on Fontana Lake with surprisingly good results when the complex hydrodynamics of the reservoir are considered. Orlob made the following conclusions from his study:

1. The transfer of energy into deep stratified impoundments is accomplished by four primary mechanisms: advection, direct solar insolation, convective mixing associated with cooling at the surface and "effective diffusion" identified with momentum transfer within the water body.

2. The transfer of energy from the epilimnion to the hypolimnion by diffusive mechanisms is limited at the thermocline by a strong density gradient.

3. A one-dimensional mathematical representation of energy transfer processes provides a satisfactory means of characterizing the thermal behavior of deep impoundments of the low volume - high discharge type.

4. Reservoir thermal behavior over annual or diurnal cycles can be simulated with a mathematical model using as input information continuous records of hydrologic, meteorologic, and climatologic conditions of the system.

Using a statistical approach for the energy balance, and assuming the eddy conductivity, Velz et al. (1966) derived temperature distributions in a reservoir that appeared quite reasonable. Wunderlich and Elder (1967) have proposed a simple graphical technique for determining temperature distribution in reservoirs that is quite useful for preliminary studies. The authors have utilized this method for predicting temperatures downstream from a proposed pumped storage project with apparent success (Krenkel, et al., 1967).

It is of interest to note that Dake and Harleman (1969) have successfully simulated the development of thermal stratification under laboratory conditions. Incoming radiation was assumed to be partially absorbed at the water surface, the remainder being absorbed exponentially beneath the surface. Heat was also assumed to be conducted downward by molecular diffusion. The artificial radiation source utilized was from mercury vapor and infrared lamps.

It should be noted that the real deficiency in any of these analytical models describing temperature distributions lies in the use of an assumed vertical diffusion coefficient. Dake and Harleman concluded that a general analytical approach should include the effect of internal radiation absorption. Neglect of mechanisms causing radiation absorption will lead to incorrect values of the diffusivity, as has been demonstrated in the literature (Dutton and Bryson, 1962; Orlob, 1965; Bachmann and Goldman, 1965). Again quoting Dake and Harleman, "there exists no satisfactory method of specifying a time and depth functional relation for the eddy diffusivity that could be used in a predictive mathematical model".

C. Heat Dissipation: Rivers

The computational methodology for the prediction of stream temperature in rivers differs somewhat from that used for reservoirs because of the difference in their physical characteristics. Because of the dynamic nature of a river, relatively short periods must be used to account for diurnal fluctuations in meteorological phenomenon. Allowance must also be made for stream velocity and changes in hydraulic geometry.

There are two currently used methods for predicting stream temperatures. One method uses the energy budget and the other uses a combination of an energy budget or other method to determine the steady-state, equilibrium, temperature of the stream and subsequent imposition of the transient temperature, which is assumed to decay downstream in an exponential manner.

1. Energy Budget Approach

Schroepfer (1961) converted heat exchange quantities to incremental temperatures and applied the energy budget to the Mississippi and Minnesota rivers.

His relationship was:

$$T_A + \frac{0.1855}{Q} H_A + \left[\frac{0.00445\ A}{Q}\right] \Big[H_S - (0.3253)(10 + W)(V_w - V_a) - (0.16)(5 + W)(T_w - T_a) - 1.1\,(T_W - T_a) \Big] = T_B \qquad \text{VI-13}$$

where:

T_A = River temperature at A, °F

T_B = River temperature at B, °F

A = Water surface area, 1000 ft^2

H_A = Thermal additions (power plants), mega BTU/day

Q = River flow, cfs

W = Mean wind velocity, MPH

H_S = Solar radiation, BTU/ft^2/hr

V_w = Saturation water vapor pressure at the mean temperature of the water surface, mm Hg

V_a = Partial pressure of water vapor at the temperature and relative humidity of the surrounding air, mm Hg

T_w = Mean water temperature, °F

T_a = Mean air temperature, °F.

Application of this equation to several stretches of river proved to be reasonably successful when compared to observed data, both on naturally heated streams and those affected by a heated discharge.

Raphael (1962) presented the following mathematical model, applicable to lakes and rivers:

$$\frac{dt_w}{d\theta} = \frac{Q_t A + m_i \ (t_i - t_w)}{m_w} \qquad \text{VI-14}$$

where:

θ = time

m_w = total mass of lake

t_w = mean temperature of lake

m_i = inflow water mass

t_i = inflow water temperature

A = lake surface area

Q_t = total surface heat transfer per unit of time.

Substitution of volumes for mass and solution for given increments of time yields a simplified and workable equation. For application to river work, the outflow temperature of a reach is assumed to be the inflow temperature of the subsequent downstream reach. The article exemplifies the method by using a small reservoir and a river.

Messinger (1963) used the energy budget approach to predict the temperature profile of a heated stream in the Susquehanna River and found large discrepancies in the results. A conventional energy budget approach was utilized; however, he attributed the errors to inadequacies in the measurement of solar and atmospheric radiation. Shading of the river by trees and hills was assumed to be the major source of error.

Garrison and Elder (1965) developed a water temperature prediction model based on fundamental laws of physics and verified its use on two sets of field data. The complete conservation of energy balance utilized results in the following equation:

$$u\rho cT\Delta y\Delta z - \left[u\rho cT + \frac{\partial\ (u\rho cT)}{\partial x}\Delta x\right]\Delta y\Delta z + v\rho cT\Delta x\Delta z - \left[v\rho cT + \frac{\partial\ (v\rho cT)}{\partial y}\Delta y\right]\Delta x\Delta z + w\rho cT\Delta x\Delta y - \left[w\rho cT + \frac{\partial\ (w\rho cT)}{\partial z}\Delta z\right]\Delta x\Delta y + \Sigma Q\Delta x\Delta z = \frac{\partial}{\partial t}(\rho cT\Delta x\Delta y\Delta z) \qquad \text{VI-15}$$

where

$\Sigma Q = Q_s - Q_{rs} + Q_a - Q_{ra} - Q_b - Q_e - Q_L - Q_h + Q_{ad} - Q_c$

u,v,w = velocity components in x,y,z directions

$\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$ = rates of change in x,y,z directions

ρ = Mass density of water

T = Mean temperature of water in control volume

Q_s = Rate of heat flow into control volume from solar radiation

Q_{rs} = Rate of heat flow out of control volume: reflected solar radiation

Q_a = Rate of heat flow into control volume from atmospheric radiation

Q_{ra} = Rate of heat flow out of control volume: reflected atmospheric radiation

Q_b = Rate of heat flow out of control volume from back radiation

Q_e = Rate of heat flow out of control volume: direct evaporation

Q_L = Rate of heat flow out of control volume, latent heat loss

Q_h = Rate of heat flow out of or into control volume by conduction

Q_{ad} = Rate of heat flow in or out of control volume, rainfall or tributary flow

Q_c = Rate of heat flow in or out of control volume: bed conduction

B = Water surface width

A = Cross-sectional area

y_o = Mean flow depth based on surface width

t = Time

c = Specific heat of water

Introduction of turbulent diffusion concepts, using short stream lengths, 24 hour time averages and steady-state flow conditions, reduced equation VI-15 to:

$$\frac{T}{T_o} = \frac{t}{T_o U} \frac{\Sigma Q}{c\rho y_o} + 1 \qquad \text{VI-16}$$

which states that the space-average dimensionless water temperature over a 24 hour cycle of any distance x from a reference station, $x = o$ in which $T = T_o$, is directly proportional to the product of ΣQ and x and inversely proportional to the product of T_o, U, c, ρ, and y_o.

The results of two field measurements showed excellent agreement of the observed temperature values and the proposed theory, which applies to the well mixed conditions existing at the test sites. This model appears to have great potential.

2. Exponential Decay of Transient Temperatures

LeBosquet (1946) proposed a mathematical basis for predicting heat loss in a flowing stream using river flow, temperature differential between water and air, hydraulic characteristics and a heat loss coefficient. While the method appears to be quite useful, it is somewhat limited because the value of the heat loss coefficient must be obtained from field observations. LeBosquet found the coefficient to vary from 6 to 18 BTU/ft^2/hr/°F of excess water temperature over air.

The mathematical model proposed is:

$$\frac{dF}{dt} = -\frac{KA_sF}{L} \qquad \text{VI-17}$$

where:

K = Heat loss coefficient, BTU/ft^2/hr/°F of excess temperature of water over air

F = Excess temperature of water over air at distance, D miles, °F

A_s = Surface area, ft^2

L = Weight of water, lbs

Integration and simplification of this equation yields:

$$K = \frac{Q \log_{10} \frac{F_A}{F}}{0.0102\ WD} \qquad \text{VI-18}$$

where:

Q = Average discharge, cfs

F_A = Initial excess temperature, °F (water over air)

W = Average stream width, ft

D = Reach distance, miles

It should be noted that the driving force utilized by LeBosquet is incorrect, inasmuch as the water will tend to approach some equilibrium water temperature rather than the temperature of the air.

Gameson et al., (1960-61), made an exhaustive study on heated discharges into the Thames Estuary and proposed the following mathematical model describing the process:

$$\frac{d\theta}{dt} = -\frac{f}{z}\theta \qquad \text{VI-19}$$

where:

θ = initial temperature increment

f = exchange coefficient

z = average river depth

t = time

Using statistical methods, they defined the natural or equilibrium temperature, T_E, as:

$$T_E = 0.5 + 1.109\ Ta \qquad \text{VI-20}$$

where:

Ta = air temperature, °C.

The solution to this equation utilized was:

$$\theta_t = \theta_o \exp - \int_o^t \frac{f}{z}\, dt \qquad \text{VI-21}$$

where:

θ_o = initial excess temperature

θ_t = excess temperature after a time length equal to two tides.

Values of the exchange coefficient for the Thames Estuary were found to average approximately 4 cm/hr. Gameson et al. (1959) utilized the same model on another study on the River Lea, which clearly demonstrated the profound effect of the heated discharge on the thermal regime of the river. The exchange coefficient in this case was found to vary from 1.66 to 3.83 cm/hr. This study concluded that the exchange coefficient was unrelated to wind velocity, which is obviously erroneous.

It is interesting to note that the model proposed is similar to that utilized by English workers to describe reaeration and thus demonstrates the effect of turbulence on heat dissipation.

Velz and Gannon (1960) assumed that the rate of temperature change is directly proportional to the rate of heat loss from the water surface,

$$\frac{dT_w}{dt} = - \frac{H}{62.4h} \qquad \text{VI-22}$$

Their solution was:

$$A = - 224,640 \int_{T_1}^{T_2} \frac{dT_w}{\alpha(V_w - V_e) + \beta(T_w - E)} \qquad \text{VI-23}$$

where:

A = surface area of the river between the points where $T_w = T_1$ and $T_w = T_2$, ft^2/cfs stream flow;

V_w = saturation vapor pressure corresponding to surface temperature T_w, in.Hg;

V_E = saturation vapor pressure corresponding to surface temperature E, in. Hg;

E = equilibrium temperature, °F; (unknown)

α = $0.00722\ H_v\ C(1. + 0.1\ W)$;

T_w = water temperature, °F;

t = time, hr;

H = rate of heat loss from the water surface, BTU $ft^{-2}\ hr^{-1}$;

b = depth of the river, ft;

62.4 = product of the water density and heat capacity; BTU $ft^{-3}\ °F^{-1}$;

β = $(1.8 + 0.16\ W)$;

H_v = latent heat of vaporization, BTU lb^{-1}; at assumed water water temperature;

C = evaporation coefficient ranging from 10-15;

W = windspeed at 25 feet above water surface, mph.;

T_a = air temperature, °F;

V_a = vapor pressure of the air, in. Hg; and

H_s = heat gain by solar radiation; BTU $ft^{-2}hr^{-1}$ (measured).

They derived a relationship for the long-term unheated equilibrium water temperature as follows:

$$(1.8 + 0.16\ W)\ E + 0.00722\ H_vC\ (1 + 0.1W)\ V_E =$$
$$(1.8 + 0.16\ W)\ T + 0.00722\ H_vC\ (1 + 0.1W)\ V_a + H_s \qquad \text{VI-24}$$

This equation is solved by successive approximation, assuming values for the equilibrium temperature and using Meyer's evaporation formula. The resulting value of E, the equilibrium water temperature is then used in the following working equation to estimate the required water surface area for cooling:

$$A = -224,640 \sum_{T_1}^{T_2} \frac{\Delta T_W}{\alpha(V_W - V_E) + \beta(T_W - E)} \qquad \text{VI-25}$$

The total increment of temperature between the initial heated condition and the desired downstream temperature is divided into equal increments (ΔT_W) with T_W and V_W the mean temperature and mean saturation vapor pressure in each increment. Long-term weather averages are used in the computations.

Duttweiler (1963) proposed a mathematical model for stream temperature by equating the heat gained in an incremental reach of stream to the time change in enthalpy of the water in the reach. As in previous studies, Duttweiler assumed that the time rate of temperature increase is proportional to the deficit between the actual temperature and some equilibrium temperature. The resulting one dimensional model was:

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} = \frac{1}{\rho c}\,\frac{\lambda}{z}\,(T_E - T) \qquad \text{VI-26}$$

where:

T = water temperature;

t = time;

v = velocity at x and t;

x = distance along the stream;

ρ = water density;

c = heat capacity of water;

λ = parameter dependent upon atmospheric conditions;

z = hydraulic depth of the stream or the cross-sectional area divided by the surface width; and

T_E = equilibrium water temperature.

Using Lagrangian coordinates, the expression for river temperature becomes:

$$\frac{dT}{dt} = \frac{1}{\rho c} \quad \frac{\lambda}{z} \quad (T_E - T) \qquad \text{VI-27}$$

and its position may be found from:

$$X - X_o = \int_{t_o}^{t} vdt \qquad \text{VI-28}$$

It is obvious that $\lambda(T_E - T)$ is the net heat transfer rate through the air-water interface, ΔH, if evaporation losses, Q_w, are excluded, or:

$$\lambda(T_E - T) = \Delta H + Q_w \qquad \text{VI-29}$$

Duttweiler presents values for λ based on published meteorological data and gives solutions to equations VI-26 and VI-28 in integral form.

Edinger and Geyer (1965) proposed that the net rate of heat transfer through the air water interface was represented by:

$$\Delta H = -K(T_s - E) \quad , \qquad \text{VI-30}$$

where:

ΔH = net heat transfer rate through air-water interface, BTU/ft^2/day.

E = equilibrium temperature, °F.

T_s = water surface temperature, °F.

K = exchange coefficient, BTU/ft^2/day/°F.

Nomograms for determining E when K is known were presented and methodology defining the exchange coefficient were given.

Assuming that the river reach considered was at steady state, they proposed one-dimensional and two-dimensional models for temperature prediction. The one dimensional model was:

$$\rho C_p U d \frac{\partial T}{\partial x_1} = -K (T - E) \qquad \text{VI-31}$$

and the two-dimensional model, which accounts for lateral mixing and advection was:

$$U \frac{\partial T}{\partial x_1} + D_2 \frac{\partial^2 T}{\partial x_2^2} + \frac{K}{\rho C_p d} (T - E) = 0 \qquad \text{VI-32}$$

The solution presented for equation VI-31 was:

$$\frac{T - E}{T_m - E} = \exp \left[- \frac{K x_1}{\rho C_p U d} \right] \qquad \text{VI-33}$$

and for equation VI-32:

$$\frac{T - E}{T_o - E} = \exp \left[- \frac{C_2 + \alpha^2}{C_1} x_1 \right] \exp [-\alpha x_2] \frac{\exp [-2\alpha(W - x_2)]}{1 + \exp [-2\alpha W]} \qquad \text{VI-34}$$

where:

ρ = water density, lb/ft^3;

C_p = heat capacity of the water, BTU/lb;

U = mean velocity of the stream at x_1, ft/day;

d = mean depth of the stream at x_1; ft

$\frac{\partial T}{\partial x_1}$ = longitudinal temperature gradient; °F/ft.

T = water temperature; °F

x_1 = longitudinal distance on the stream; ft

D_2 = lateral mixing coefficient, assumed constant over the channel, $ft^2 day^{-1}$;

x_2 = distance across the stream, ft;

T_o = temperature of a thermal discharge at the point $x_1 = x_2 = 0$, °F;

C_1 = U/D_2, ft^{-1};

C_2 = $\frac{K}{C_p d D_2}$, ft^{-2};

α = coefficient depending on boundary conditions

W = stream width, ft.

T_m = water temperature at upstream end of reach, °F

Edinger and Geyer's study includes basic concepts of the energy balance, applied aspects with respect to reservoirs and rivers, and operational methods. Heated water investigations are discussed, including a discussion on instrumentation and the mechanisms of heat exchange with the atmosphere. Several useful models of temperature distribution in reservoirs and rivers are presented and ensuing applications of the methods presented demonstrate the methodology. However, the difficulties encountered in applying the nomograms are not sufficiently stressed. Also, the systems studied are primarily steady-state in nature or the temperatures are known and the transfer coefficients are computed rather than the usual case of attempting to predict the temperatures.

Examination of the non-English literature demonstrates approaches similar to that of LeBosquet, where the temperature downstream from a power plant effluent is assumed to decay exponentially and "river constants" are derived from field measurements. The real problem with this type approach, of course, is the validity of the assumptions; i.e., steady state conditions, non-varying river flows, vertically and laterally uniform temperature distributions, and the requirement that the equations apply only downstream of the river section, where complete mixing is achieved. Probably the most notable of these studies are Halleaux (1964), Goubet (1965, 1966), and Mandelbrot (1964). Additional investigations demonstrating the applicability of energy budget methods to river temperature prediction include Fleuret (1968) and Gras (1968).

The work of the advanced seminar at Johns Hopkins University should also be mentioned (Anon. 1962), where the following conclusions were drawn:

1. The quantitative determination of heat transfer within a natural body of water, or between a body of water and its surroundings, is extremely difficult and complex.

2. Temperature change within a body of water is primarily effected by the operation, either independently or jointly, of two mechanisms: turbulent mixing of two or more batches of water of different temperatures eventually resulting in a single batch of water at the weighted mean temperature; and heat exchange of the water with its surroundings, primarily the atmosphere, governed by the mechanisms of conduction, convection, evaporation, condensation, and radiation.

3. Temperature change is effected to only a minor degree by molecular diffusion and conduction within the body of water.

4. Forecasting of heat loss from artificially heated batches of water may be attempted by use of certain of three principal techniques depending on the availability of data and on the adherence of the specific situation to certain specialized requirements.

5. Where heat is discharged to a stream from a point source, and where complete vertical mixing may be assumed, turbulent mixing may be considered the dominant heat transfer mechanism until horizontal mixing is complete; that is, until that downstream transect is reached where the cross-section temperature is uniform from bank to bank.

6. Assuming that there is no horizontal temperature gradient, either as a result of effective turbulent mixing as described in No. 5 above, or as a result of heat discharge from a thoroughly diffused source, and assuming complete vertical mixing, heat loss may be evaluated by either use of the heat budget theory method or equilibrium temperature theory method.

7. The complexity of the heat budget theory method makes this method infeasible for field use except where extremely precise, reliable, and rugged instrumentation is available.

8. At present, not all of the instrumentation required by No. 7 above is available.

9. The relative simplicity of the equilibrium theory method, coupled with its feasibility for use under field conditions suggests its use for forecasting heat loss both in specific field situations and in generalized design situations using combinations of ambient conditions selected according to statistical considerations.

Jaske (1966, 1968) presents computer programs for determining the temperature distribution in the Columbia River. Variation in hydraulic characteristics of the river was accounted for by dividing the river into a central channel and two side channels and applying an energy budget similar to Raphael's.

Dingman et al (1968) presented a method for calculating the length of ice-free river that develops below a power plant during the winter. Their method uses daily averages of meteorologic variables and "by use of a computer program allows the use of several of the many previously developed empirical and semi-empirical formulae for the heat budget terms."

Finally, the work of Roesner (1969) should be mentioned because of the somewhat unique application of the surface renewal theory as proposed by Danckwerts (1951) to account for the effects of turbulence on heat transfer across the interface. Roesner developed two models to describe the net rate of heat transfer through the interface of a flowing stream. The only difference in the models was the depth of the fluid elements utilized in the surface renewal scheme. One model assumed that the elements were infinitely deep and the other assumed that the depth was limited to the thickness of the film. Application of the models to field data was favorable and the author concluded that, "while turbulence does significantly affect the net rate of heat transfer through the air-water interface, it probably does not significantly affect short term temperature prediction. However, neglecting to account for the turbulence level introduces a bias in the time rate of temperature change so that long term averages in the order of a week or month may be significantly affected during periods of warming or cooling."

D. Equilibrium Temperature

If a body of water at a given initial temperature is exposed to a given set of constant meteorological conditions, it will tend to approach another particular temperature asymptotically, approximately in an exponential fashion. It may warm by gaining heat or cool by losing heat. Theoretically, after an infinite period of time the temperature will become constant, and the net heat transfer will be zero. This final temperature has been called the equilibrium temperature, E. At equilibrium, the heat gained by absorbing solar radiation and long-wave radiation from the atmosphere will exactly balance the heat lost by back radiation, evaporation, and conduction. That is:

$$H_s + H_a + H_b + H_e + H_c = 0 \Big|_{T = E} \tag{VI-35}$$

In actuality, the water temperature rarely equals the equilibrium temperature because the equilibrium temperature itself is constantly changing as the local meteorological conditions change. The equilibrium temperature will generally rise during the day as solar radiation is highest, and fall to a minimum at night when solar radiation is absent.

A daily average equilibrium temperature may be computed using daily average values of radiation, temperature, wind speed, vapor pressure, etc., and this daily average will reach a maximum in midsummer and a minimum in midwinter. Other time periods, such as monthly, may also be used for averaging. Since the actual water temperature always tends to approach, but lag behind the equilibrium temperature, it will usually be less than equilibrium in the spring when temperatures are rising, and greater than equilibrium in the fall when temperatures are falling.

During a one day period, the equilibrium temperature usually varies from above the actual water temperature during the day to below the actual water temperature at night, forcing the water temperature to also assume a similar cycle. The annual variation of temperature has been fitted by a sine curve by Ward (1963),and Duttweiler (1963) presents a review of attempts to utilize a sine function to fit daily and yearly temperature fluctuations. As stated by Duttweiler, "It is not suggested that the diurnal variation, for example, be considered in analyzing stream conditions over several months, nor that the annual variation be considered in analyzing stream conditions over a few hours. However, the presence of these "cycles" should be kept in mind, especially when dealing with stream characteristics which are particularly sensitive to temperature change."

It is appropriate to use the excellent summary prepared by Roesner (1969) which compares several of the previously described models:

"Although the models discussed in this section appear quite different in the form of their solutions, some of them are actually quite similar and could be expected to produce nearly the same answers when applied to a given problem. For example, it can be shown that Schroepfer's model and the Advanced Seminar model differ only in the following respects:

1. Method of computing long-wave atmospheric radiation;
2. Units and empirical coefficients used; and
3. Inclusion of heat exchange by eddy diffusion by the Advanced Seminar.

By comparing differential forms, it can be shown that the models of Gameson, Gibbs, and Barret, Velz and Gannon, Duttweiler, and Edinger and Geyer are very similar. For ease of comparison, the models are collected in Table VI-1. Consider a river reach which is receiving a thermal discharge and observe the following (assuming consistent units):

1. If mean daily or monthly temperatures are used for the natural stream temperature, the equilibrium temperature of Duttweiler (T_E) and of Edinger and Geyer (E) can be considered equal to the natural river temperature. Thus $(T - T_E)$ and $(T - E)$ can be equated to Gameson, Gibbs, and Barnet's excess temperature θ, i.e.,

$$\theta = (T - T_E) = (T - E).$$

2. The time of travel t, and the longitudinal distance along the stream x, are related as

$$\frac{dx}{dt} = U$$

where U is the mean velocity of the stream at the point x; thus

$$\frac{dT}{dt} = U \frac{dT}{dx} .$$

3. If the time base for travel time is short compared to the time interval for which the natural stream temperature is averaged, then E and T_E can be considered constant and

$$\frac{d\theta}{dt} = \frac{d(T - T_E)}{dt} = \frac{dT}{dt}$$

and

TABLE VI-1

COMPARISON OF STREAM TEMPERATURE PREDICTION MODELS

Gameson, Gibbs, and Barrett

$$\frac{d\theta}{dt} = -\frac{f}{z}\theta$$

where θ = excess of water temperature over natural water temperature;

f = exchange coefficient;

z = mean river depth.

Velz and Gannon

$$\frac{dT_w}{dt} = -\frac{H}{62.4b}$$

where T_w = water temperature;

H = rate of heat loss from water surface;

b = river depth.

Duttweiler

$$\frac{dT}{dt} = \frac{1}{\rho c}\frac{\lambda}{z}(T_E - T)$$

where T = water temperature;

λ = parameter dependent on atmospheric conditions;

z = hydraulic depth;

T_E = equilibrium temperature.

Edinger and Geyer

$$C_p U d \frac{\partial T}{\partial x_1} = -K(T - E)$$

where T = water temperature;

U = mean stream velocity;

d = mean stream depth;

K = exchange coefficient;

E = equilibrium temperature.

$$\frac{d\theta}{dt} = \frac{d(T - E)}{dt} = \frac{dT}{dt} = U \frac{dT}{dx} .$$

4. By use of items (1) and (3) above, it is observed that

$$f = \frac{\lambda}{\rho C} = \frac{K}{\rho C} .$$

The essential difference is that λ and K are defined in terms of atmospheric variables and parameters, while f is strictly empirical.

5. It is observed that the net rate of heat loss from the river H, in Velz and Gannon's model can be equated as

$$H = \lambda (T - T_E) = K(T - E) .$$

Thus for the conditions stated in item (1) the basic models of Gameson, Gibbs, and Barnett; Duttweiler; Edinger and Geyer; and Velz and Gannon can be considered identical. The solutions however will not give identical answers because of the different approaches taken in integrating the individual models. The other models reviewed here are individualistic either in their derivation or in the methods used to obtain the working equation and thus cannot be compared.

The models described above define the state of development of temperature prediction equation for streams. Note that all the models presented here are one-dimensional except for Edinger and Geyer's two-dimensional model which is quite simplified."

E. Remote Sensing of Thermal Pollution

Though this review does not concern itself with instrumentation, it was thought advisable to briefly note the work already done on the use of remote sensing techniques to determine the discharge and spread of heated waters. Perhaps most outstanding has been the use of the NIMBUS satellite high resolution infrared imagery to detect currents, upwellings, and temperature contours of the Great Lakes (National Council on Marine Resources, 1967). Though some of the needed information in this area is still classified, sufficient data is known to enable one to use the technique and its airplane and laboratory versions to study the patterns of temperature distribution on water surfaces. Present capabilities in infrared imagery (not photography) are such that a number of commercial firms are available on a contract basis to provide complete service. Infrared wave lengths, in the 1.5 to 14 micron range are used in hydrologic studies because in this region the infrared energy emitted by land and water bodies is a maximum and atmospheric absorption is at a minimum (Lukens, 1968). A typical scanner is sensitive to 1/4° Centigrade surface temperature changes and can be calibrated with surface instrumentation to 1/2° Centigrade. Infrared radiometers sensitive to 0.01° Centigrade are not uncommon, but obtain data at such a low rate to be useless for large scale studies (Parker and Wolff, 1965).

A brief evaluation of the use of remote sensors in hydrology was presented at the International Conference on Water for Peace (Robinove, 1967). At that time, photographic sensors were still most favored because of the easy interpretability and the minimum data reduction and specialized training needed for their use. Infrared sensors offer hope of great things in thermal pollution work, but are hampered in a quantitative - not qualitative - sense at present by problems of emissivity measurement. In any case, infrared imagery is only a function of the surface temperature of the waters and does not give any indication of the thermal profile.

An earlier paper provided in detail a large amount of data on patterns of thermal pollution, by use of aerial photography and included a number of pictures of power plant outfalls (Strandberg, 1962).

F. Research Needs

1. Mathematical Modeling

Probably the most critical need in the prediction of heat dissipation is for accurate field data that will substantiate or refute the various methematical models proposed. While empiricism is a good expedient, it promotes development of a new mathematical description for each problem encountered. Obviously, a generalized model, based on sound theoretical principles, and proven by good field measurements, would be the utopia in the prediction of heat dissipation. A rigorous three dimensional mathematical model for this purpose should be given high priority.

The various assumptions inherent to the many models proposed should be field tested for validity and application. Examples are: steady state conditions, non-varying river flows, vertically and laterally uniform temperature distributions and complete mixing.

Only minimal consideration has been given so far to the time varying problem. Further work needs to be done to establish predictive methods for transient conditions in reservoirs and in rivers.

Little work has been done on the temperature distribution following the startup or shutdown of power plants.

2. Instrumentation

A real critical question to be answered with respect to energy balance calculations involves the level of sophistication required for measurement of the variables. Obviously, the instrument chosen for a particular measurement should be just adequate to yield usable results. The use of pyrheliometers to measure incident and reflected solar radiation, and Gier and Dunkle flat plate radiometers to measure incident total radiation, should be compared with the results obtained by the Cummings Radiation Integrator, which is considerably less expensive.

It would be highly desirable to install a complete first class meteorological station at a selected site, simultaneously install inexpensive types of instrumentation and compare the resulting measurements on a statistical basis. A sensitivity analysis to determine the adequacy of each measurement for the energy balance would be mandatory. For example, what accuracy of a particular measurement would yield acceptable values for the energy balance and how significant would be the resulting error?

3. Use of Data from Meteorological Stations

A major problem existing with respect to analyzing a given site for heat exchange characteristics lies in the absence of meteorological data. The real question to be answered here is with regard to the transposition of meteorological data from the nearest meteorological station having the information desired. Obviously, considerable differences in wind measurements can occur in a very short distance; however, the distance at which meteorological parameters become questionable is yet to be established. Velz (1966) has transposed meteorological data, including air temperature, wind velocity, vapor pressure, relative humidity and solar radiation to a distant site with apparent success.

A worthwhile endeavor would involve comparing the data collected at first order meteorological stations with each other and with similar measurements made at varying distances and conditions from the station. Again, a sensitivity analysis of these variables would be most useful, inasmuch as considerable savings could be realized in site analysis if weather bureau data could be utilized. Data such as presented by Velz (1966) should be summarized for all first order weather bureau stations and subjected to rigorous statistical analysis for use by the practicing engineer or regulatory agency.

4. Data Collection Requirements

Evaluation of the frequency of data collection required to yield reasonable results is direly needed. A critical question is involved with the minimum period of time over which measurements should be taken and calculations made. It is also pertinent to determine the effects of diurnal variations in these parameters. Answers to these questions could probably be partially provided by analyzing existing data in an appropriate manner; however, resort to field measurements, designed specifically to answer these questions should be made. A sensitivity analysis on the results would again provide answers to the degree of complexity of instrumentation and computations required.

Another factor that needs evaluation in this regard is the effect of shading by vegetation on the data collected, inasmuch as discrepancies in many energy balance studies have been attributed to this phenomenon.

5. The Exchange Coefficient

The constants utilized in calculating the exchange coefficient need substantiation. Since it is a function of meteorological parameters, it is not necessarily constant and it would be useful to know the error incurred by assuming it to be constant.

The effects of turbulence on the rate of heat dissipation also should be elucidated. All indications are such that the mechanism of heat transfer in flowing rivers is similar to that of gas transfer. This can and should be demonstrated in the laboratory. The turbulence level at which this mechanism becomes important should be established and thus separated from other effects.

It is expected that heat transfer will be relatively independent of the turbulence intensity below some plateau level, above which a direct dependence will occur.

6. Pre-Impoundment Prediction

It is often necessary to predict temperature distributions in an impoundment prior to its construction, to determine effects on water quality. While Orlob (1967) has gained insight into the field problems of such predictions and Dake and Harleman (1969) have simulated reservoir stratification under laboratory conditions, considerable work remains to be done before reliable predictions can be made. For example, evaluation of the vertical diffusion characteristics of heat in a reservoir leaves much to be desired.

High priority should be given to this problem, both on a laboratory and field scale.

7. Heating Up of Waters

At present, there are few sites available where the average temperature rise in the river exceeds 5°F. With such low temperature differences, it is difficult to separate the effect of various components of the energy budget. However, the inverse case, where cool waters are released from deep reservoirs and heat up as they move downstream, does at times result in temperature rises of as much as 20°F. Therefore, work should be initiated on these special cases to determine the effect of the various components of the energy budget in inducing temperature rises.

Bibliography

Anderson, E. R., (1964), "Water Loss Investigations: Lake Hefner Studies." Technical Report, U. S. Geological Survey, Professional Paper 269.

Anderson, E. R., et al., (1960), "A Review of Evaporation Theory and Development of Instrumentation." U. S. Navy Electronics Laboratory, Report 159.

Angström, A., (1920), "Applications of Heat Radiation Measurements to the Problems of Evaporation from Lakes and the Heat Convection at Their Surfaces." Geografisca Annual, *2*.

Anon., (1962), "Heat Dissipation in Flowing Streams." Advanced Seminar Report, Department of Sanitary Engineering and Water Resources, Johns Hopkins University.

Bachmann, R. W. and Goldman, C. R., (1965), "Hypolimnetic Heating in Castle Lake, California." *Limnology and Oceanography*, 10(2).

Bergstrom, R. N., (1968), "Hydrothermal Effects of Power Stations." Paper presented at ASCE Water Resources Conference, Chattanooga, Tennessee.

Boyer, Peter B., (1963), "Method of Computing Average Reservoir Temperature, Water Temperature, Influences and Effects." *Proceedings, 12th Pacific Northwest Symposium on Water Pollution Research*, Corvallis, Oregon.

Dake, J. M. K., and Harleman, D. R. F., (1969), "Thermal Stratification in Lakes: Analytical and Laboratory Studies." *Water Resources Research*, *5*, 484.

Danckwerts, P. V., (1951), "Significance of Liquid Film Coefficient in Gas Absorption." *Industrial and Engineering Chemistry*.

Delay, W. H. and Seader, J., (1963), "Temperature Studies on the Umpqua River, Oregon: Water Temperature, Influences and Effects." *Proceedings, 12th Pacific Northwest Symposium on Water Pollution Research*, Corvallis, Oregon.

Dingman, S. L., Weeks, W. F., and Yen, Y. C., (1968), "The Effects of Thermal Pollution on River Ice Conditions." *Water Resources Research*, Volume 4, No. 2, April.

Dutton, J. A., and R. A. Bryson, (1962), "Heat Flux in Lake Mendota." *Limnology and Oceanography*, 7(1), 80.

Duttweiler, D. W., (1963), "A Mathematical Model of Stream Temperature." *Thesis*, John Hopkins University.

Edinger, J.E., (1965), "Heat Exchange in the Environment." The Johns Hopkins University.

Edinger, J.E., and Geyer, J.C., (1965), "Heat Exchange in the Environment." Cooling Water Studies for Edison Electric Institute, Johns Hopkins University, June.

Fleuret, J., (1968), "Computer Techniques for Estimation of the Cooling Capacity of a River." Electricitè de France, HC-091-68/No.34, (Estimation de la Capacite de Refrigeration D'une Riviere Par Calcul Automatique)

Frenkiel, J., (1963), "On the Accuracy of the Combined Energy-Budget and Mass-Transfer Method." Journal of Geophysical Research, 68, September.

Gameson, A.L.H., Gibbs, S.W., and Barrett, M.J., (1959), "A Preliminary Temperature Survey of a Heated River." Water and Water Engineering, 63, June.

Gameson, et al., (1960 & 1961), "Effects of Heated Discharges on the Temperature of the Thames Estuary." Parts I and II, Combustion.

Garrison, J.M. and Elder, R.A., (1965), "A Verfied Rational Approach to the Prediction of Open Channel Water Temperatures." International Association for Hydraulic Research, Leningrad.

Goubet, A., (1965), "Influence des Centrales Thermiques Sur Les Cours D'Eau." Electricitè de France, Paris, France.

Goubet, A., (1966), "Problemes Poses Par La Refrigération Naturelle Des Cours D'Eau." Electricitè de France, Paris, France.

Gras, R., (1968), "Cooling of Classical Thermal or Nuclear Central Stations Power Plants by Transfer Across Water Surfaces and by Rivers." Electricitè de France, HC-091-68/No. 9. (Refrigeration Des Centrales Thermiques Classiques ou Nuclearies Par Plan D'eau et Rivieres.)

Halleaux, G., (1964), "Étude due Profil Thermique de Régime D'un Cours D'Eau." La Tribune due Cebedeau, No. 246 and 252.

Harbeck, G.E., Jr., (1953), "The Use of Reservoirs and Lakes for the Dissipation of Heat." U.S. Geological Survey, Circular No. 282.

Harbeck, G.E., Jr., (1958), "Water Loss Investigations: Lake Mead Studies." U.S. Geological Survey, Professional Paper 298.

Harbeck, G.E., Jr., (1962), "A Practical Field Technique for Measuring Reservoir Evaporation Utilizing Mass Transfer Theory." U.S. Geological Survey, Professional Paper 272-E.

Harbeck, G.E. Jr., Koberg, G.E., and Hughes, G.H., (1959), "The Effects of the Addition of Heat from a Power Plant on the Thermal Structure and Evaporation of Lake Colorado City, Texas." U.S. Geological Survey, Professional Paper 272-B.

Jaske, R.T., (1966), "An Evaluation of the Use of Selective Discharge from Lake Roosevelt to Cool the Columbia River." Battelle Northwest Laboratory, Report No. BNWL-208, February.

Jaske, R.T., and Spurgeon, J.L., (1968), "A Special Case, Thermal Digital Simulation of Waste Heat Discharges." Water Research, 2, 777.

Koberg, G.E., (1964), "Methods to Compute Long-Wave Radiation from the Atmosphere and Reflected Solar Radiation from a Water Surface." U.S. Geological Survey, Professional Paper 272-F.

Krenkel, P.A., Parker, F.L., Thackston, E.L., (1967), "The Effects of Pumped Storage at Tocks Island on Water Quality." Report to Corps of Engineers, Philadelphia District, November.

LeBosquet, A.M., Jr., (1946), "Cooling Water Benefits from Increased River Flows." Journal, New England Water Works Association, 60, 111-116.

Lima, D.O., (1936), "Pond Cooling by Surface Evaporation." Power, March, 142-144.

Lukens, John E., (1968), "Remote Sensing of Thermal Pollution." HRB-Singer Inc., 1-14.

Mandelbrot, L., (1964), "Le Refroidissement des Condenseurs des Centrales Eléctriques Thermiques." Bulletin due Centre de Recherches et D'Essais de Chatou, No. 7, 1-82.

Messinger, H., (1963), "Dissipation of Heat from a Thermally Loaded Stream." Article 104, U.S. Geological Survey Professional Paper 475-C.

Moore, A.M., (1963), "Instrumentation for Water Temperature Studies: Water Temperature, Influences and Effects." Proceedings, 12th Pacific Northwest Symposium on Water Pollution Research, Corvallis, Oregon.

National Council on Marine Resources and Engineering Development (1967), "United States Activities in Spacecraft Oceanography." U.S. Government Printing Office, 3.

Orlob, G.T., (1965), "A Mathematical Model of Thermal Stratification in Deep Reservoirs." Paper presented at the Annual Meeting of the American Fisheries Society, Portland, Oregon, September 24.

Orlob, G.T., (1967), "Prediction of Thermal Energy Distribution in Streams and Reservoirs." Report to California Department of Fish and Game, June 30.

Orlob, G.T., and Selna, (1967), "Prediction of Thermal Energy Distribution in Deep Reservoirs." *Proceedings, 6th Annual Sanitary and Water Resources Engineering Conference*, Vanderbilt University, Department of Sanitary and Water Resources Engineering, Technical Report No. 13.

Parker, D.C., and Wolff, M.F., (1965), "Remote Sensing." *International Science and Technology*, 20.

Raphael, J.M., (1962), "Prediction of Temperature in Rivers and Reservoirs." *Power Division Journal*, American Society of Civil Engineers Proceedings.

Robinove, Charles J., (1967), "Remote-Sensing Potential in Basic Data Acquisition." Water Resources Bulletin, Volume 3, No. 3, September, pp. 32-46.

Rodgers, G.K., and Anderson, D.V., (1961), "A Preliminary Study of the Energy Budget of Lake Ontario." *Journal, Fisheries Research Board of Canada*, 18, 4.

Roesner, L.A., (1969), "Mathematical Models for the Net Rate of Heat Transfer Through the Air-Water Interface of a Flowing Stream." Ph.D. Thesis, University of Washington.

Schmidt, W., (1915), "Annalen der Hydrographic und Maritimen Meteorologic." 111-124, 169-178.

Schroepfer, G.J., et al., (1961), *Pollution and Recovery Characteristics of the Mississippi River, Volume I, Part III.* Report by Sanitary Engineering Division, Department of Civil Engineering, University of Minnesota, September.

Strandberg, Carl H., (1962), "Analysis of Thermal Pollution from the Air." *Proceedings, 17th Annual Industrial Wastes Conference*, Purdue University, Lafayette, Indiana.

Sutton,.O.G., (1949), "The Application to Micrometeorology of the Theory of Turbulent Flow Over Rough Surfaces." *Royal Meteorological Society, Quarterly Journal*, 75, No. 326, October.

Sverdrup, H.U., (1937-38), "On the Evaporation from the Oceans." *Journal, Marine Research*, 1, No. 1.

Throne, R.F., (1951), "How to Predict Lake Cooling Action." *Power*, September.

Turner, J.F., Jr., (1966), "Evaporation Study in a Humid Region, Lake Michie North Carolina." U.S. Geological Survey, Professional Paper 272-G.

United States Geological Survey, (1954), "Water Loss Investigations, Lake Hefner Studies." Technical Report, Professional Paper 269.

United States Geological Survey, (1954), "Water Loss Investigations, Lake Hefner Studies." Base Data Report, Professional Paper 270.

United States Public Health Service,(1963),"Water Temperature, Influences and Effects and Control." Proceedings, 12th Pacific Northwest Symposium on Water Pollution Research.

Velz, C.J., Calvert, J.D., Deininger, R.A., Heilman, W.L. and Reynolds, J.Z., (1966), "Waste Heat Dissipation in Streams, Ponds, and Reservoirs with Application to the Duke Power Company Proposed Keowee-Jocassee Developments." Report to the U.S. Fish and Wildlife Service, April.

Velz, C.J., and Gannon, J.J., (1960), "Forecasting Heat Loss in Ponds and Streams." Journal, Water Pollution Control Federation, April.

Ward, J.C., (1963), "Annual Variation of Stream Temperature." Journal, Sanitary Engineering Division, American Society of Civil Engineers December.

World Meteorological Organization, (1966), "Measurement and Estimation of Evaporation and Evapotranspiration." Technical Note No. 83, Geneva.

Wunderlich, W.O., and Elder, R.A., (1967a), "The Influence of Reservoir Hydrodynamics on Water Quality." Proceedings, 6th Annual Sanitary and Water Resources Engineering Conference, Vanderbilt University, Department of Sanitary and Water Resources Engineering, Technical Report No. 13.

Wunderlich, W.O., and Elder, R.A., (1967b), "The Mechanics of Stratified Flow in Reservoirs." Proceedings, Reservoir Fishery Resources Symposium, University of Georgia.

CHAPTER VII - 1

MECHANISMS OF HEATED WATER DISCHARGES

There are two basic methods of discharging heated waters. The heated effluent can be discharged as a layer (subsurface or surface) or as a mixing jet. The former results in a small volume with the same temperature as the effluent (if no mixing whatsoever occurs). The latter, mixing jet, is designed to minimize the temperature rise at any point by mixing with a large part of the total volume of available water. At the end of the zone in which this mixing occurs, the final mixed temperature throughout the river cross-section should be

$$T_M = T_R + \frac{Q_P}{Q_R} \Delta T \qquad \text{VII - 1}$$

where

T_M = mixed temperature

$\Delta T = T_P - T_R$

T_P = temperature of plant effluent

T_R = temperature of ambient fluid

Q_P = plant flow

Q_R = river flow

The layered discharge can be obtained by use of a canal; frequently used, for example, by plants in the TVA system. Pipes can be used also, although for large volumes of cooling water, unless sufficient flow area were provided, significant mixing would be expected to occur. Such pipes could be at or below the water surface. The Widows Creek Steam Plant uses a series of rectangular conduits emptying into a small harbor. The condenser water may also be discharged into another water body and hence into the main receiving body. The effluent from the New Johnsonville Steam Plant (in Tennessee) empties into a coal barge harbor and thence into the main river.

Discharge for complete mixing is usually accomplished by use of a multi-port diffuser placed on the river bottom perpendicular to the flow. Harleman, Hall, and Curtis (1968) performed extensive model studies to form a basis for design of a diffuser system for the proposed Browns Ferry Nuclear Power Plant. Studies were made to determine the following: distance downstream to uniformly mixed profile, effect of jet port diameter and spacing, effect of jet angle, effect of differing steady river discharges, scour produced by the jets, upstream extension of a thermal wedge, and effect of unsteady river flows on the diffuser system characteristics. Harleman (1969) discusses these problems further.

If the cooling water is discharged as a layer, a portion will be carried downstream. A portion may also move upstream as a thermal wedge. If the mixing jet is used for discharge, an upstream thermal wedge may also form, being again subject to surface heat exchange. The downstream layer will mix laterally (and perhaps vertically) with the ambient fluid as a result of initial differences in velocity and momentum. Upon dissipation of these differences, dispersion of the heated mass will continue as a function of the processes of turbulent diffusion and mixing. Superimposed on both the wedge and downstream processes is the influence of heat exchange between water and the atmosphere. This heat exchange is the only consideration downstream from the fully mixed section.

Vertical mixing does occur in many layer discharges, though most are designed to minimize such mixing. However, if the temperature of such a layer would be too great, or too long a wedge would form, etc., the designer could choose to attempt to cause partial mixing with a resultant layer at a lower temperature. While not as rapid for heat dissipation to the atmosphere, some such benefits are retained while possibly lessening some threats to water quality.

It should be noted that there are limits to the discharge of waste heat to a water body. It has been observed that "Such techniques cannot be expected to solve the problems associated with the discharge of large heat loads into moderate volumes of receiving water. Any heated discharge which will promote excessive temperature rises will require the use of cooling devices," (Federal Water Pollution Control Administration, 1968). The limitation should perhaps be rephrased to include any situation created by heated discharges which would reduce any water quality parameter below acceptable levels.

A. Formation and Description of Warm-Water Wedges

If a heated effluent is discharged into a body of water, several situations may develop, depending on the characteristics of the receiving fluid and the discharge. Issuing with little momentum, the discharge may simply float onto the water surface; with higher momentum, the discharge (or jet) mixes with the ambient fluid to the extent dictated by the original momentum to be dissipated. If complete mixing does not occur and density gradients exist, then the flow characteristics of the receiving water are important. The heated water may be swept away downstream, or a wedge may be formed moving upstream. Treatment of the mixing problem and sweepaway conditions is noted under the section on momentum jets. In this section, we shall treat the problem of the heated wedge extending upstream above the under-lying colder water. Some mention of subsurface layers will also be made. In addition to the possible direct effect of higher temperatures on aquatic organisms, there is the possibility of recirculation of heated water through the intake channel. This not only decreases steam plant efficiency, it could lead to compounding the temperature problem. It is, therefore, important to have means for evaluating lengths, depths, etc., for these wedges. There do exist means for withdrawing colder water, such as by withdrawal beneath skimmer walls (Elder, 1958, Harleman and Garrison, 1962, and Harleman and Elder, 1965). However, even here it is necessary to know the length and depth of the wedge to predict how much warmer water might flow beneath the wall.

1. Problem Formulation - Dimensional Considerations

The wedge problem requires solution of the equations of stratified flow. Ordinary open channel flow is actually a stratified flow, with the water lying beneath a lighter fluid, the air. The heated discharge problem deals (as it has been thus far treated) with a two-layered system with hotter, lighter water above the colder water. Another application of stratified flow principles would attack the problem of a heated layer lying beneath the water surface. This (called an interflow) could occur when solar heating raises the receiving water surface temperatures to levels above that of the heated discharges. Treatment of such flows will not be discussed here in detail, because they are closely related to the two-layered solutions ordinarily studied. Appropriate extension to interflow conditions could be accomplished if a need arose. At the present, surface layers are of greater importance and more frequent occurrence.

Dimensional analysis indicates that the length as shown in Figure VII-1 can be expressed as:

$$\frac{L}{H} = f(F_\Delta, Re_\Delta, \frac{H}{B}, V_r) \qquad \text{VII-2}$$

where F_Δ = Upstream densimetric Froude number = $\dfrac{u_0}{\sqrt{\frac{\Delta\rho}{\rho} g H}}$

Re_Δ = Upstream Densimetric Reynolds number = $\dfrac{\sqrt{\frac{\Delta\rho}{\rho} g H}\; H}{\nu}$

$V_r = u_{jet}/u_o$

ν = Kinematic viscosity

B = Width of channel

It has been observed by Chikwendu and Francis (1967), and supported by other data, that the velocity ratio, V_r, only has effect on the degree of initial mixing and has no apparent influence on wedge length or shape upstream from the outlet. This quantity can, therefore, be dropped from consideration.

Implied in the above is some knowledge of friction along the interface between the two layers. This friction is usually expressed by a friction factor, f_i, determined from the Reynolds number of the lower layer:

$$Re_2 = \frac{4u_2h_2}{\nu} \qquad \text{VII-3}$$

Of special importance in this problem is the densimetric Froude number. Theoretically, just as in ordinary free surface flow, a Froude number greater than one implies that a disturbance cannot propagate upstream, since the stream velocity is greater than the velocity of propagation. Harleman (1969), Bata (1957), TVA (1966), and others

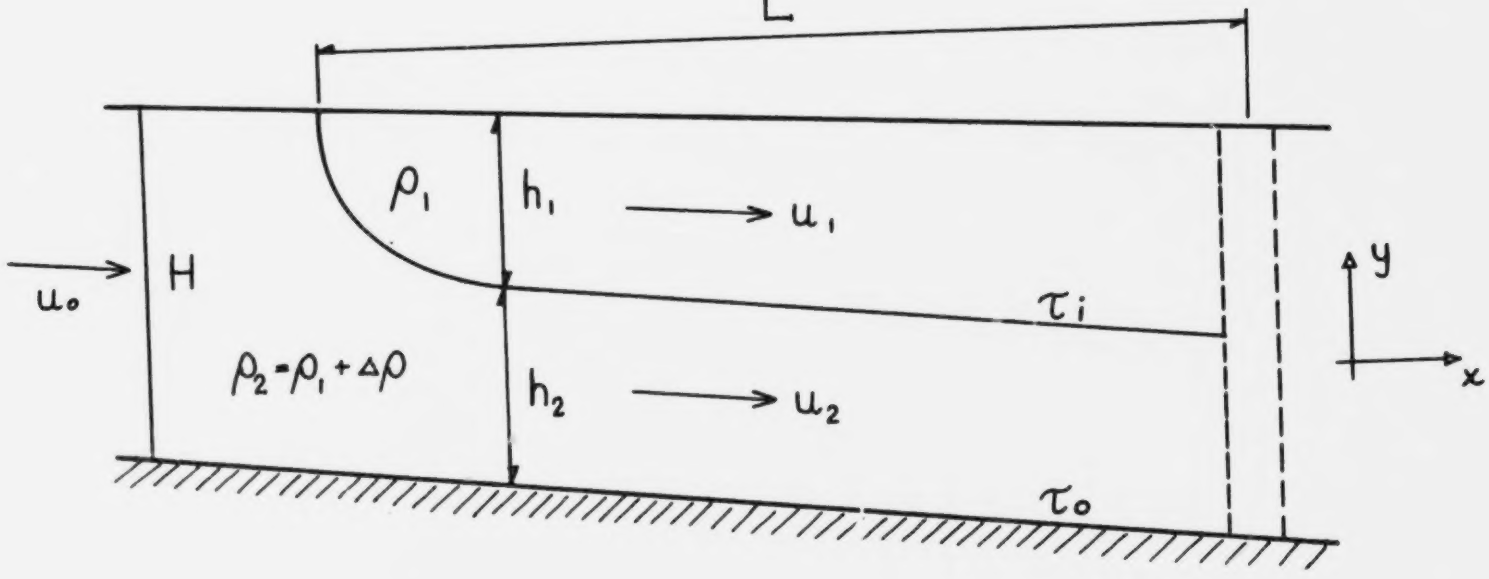

L
u_0
H
ρ_1
h_1
u_1
τ_i
$\rho_2 = \rho_1 + \Delta\rho$
h_2
u_2
τ_0
y
x

FIGURE VII - 1 SCHEMATIC DIAGRAM FOR STRATIFIED FLOW

note this theoretical value. This Froude number is based on the flow in the river between the intake and outlet, as a certain portion of the approaching river flow is diverted through the intake. Harleman (1969) states that in practice $F_\Delta > 0.7$ is sufficient to prevent a wedge. Keulegan (1957), in studies on salt wedges, found that the critical value of F_Δ was 0.75, which value was used by TVA (1966) in studies for the proposed Browns Ferry Nuclear Plant. Chikwendu and Francis (1967), studying wedges in a curved channel, extrapolated to zero wedge length at $F_\Delta = 0.83 \pm 0.02$. This latter value might have been expected to be somewhat lower, since wedge lengths for the curved channel were found significantly less than those in straight channels. However, it can still be seen that wedges should be slight or non-existent for Froude numbers of 0.7 - 0.8 or greater.

2. Basic Equations

Equations for the two layered system being studied are needed to evaluate four unknowns: u_1, u_2, h_1 and h_2. This was done by writing equations of continuity and motion for each of the two layers (Bata, 1957, and Harleman, (1969).

The shear stresses are expressed as follows:

$$\tau_i = f_i \frac{\rho}{8} |u_1 - u_2| (u_1 - u_2) \qquad \text{VII-4}$$

$$\tau_o = f \frac{\rho}{8} |u_2 \; u_2| \qquad \text{VII-5}$$

The density, ρ, used for the shear expressions is the average density of the two layers. These equations are applicable for such flows as the heated wedge and salt wedges. In fact, much of the theoretical and experimental work related to heat wedge studies has come about through application of salt wedge information.

In writing the above equations, vertical accelerations and sidewall shear effects are neglected, and only mean velocities are considered. The ordinary free surface Froude number, based on total depth and average velocity, is assumed much less than unity. Therefore, the total depth can be assumed constant relative to changes in interfacial position, or $H = h_1 + h_2 = \text{constant}$.

Other assumptions, as discussed by Harleman and Stolzenbach (1967) are:

a. One-dimensional flow in each layer. This also assumes neglect of sidewall shear and vertical acceleration. Harleman notes that the hydraulic radius may be adjusted in computing the friction factor, affording some improvement for two and three dimensional flows.

b. Uniform density in each layer. This essentially states that there is no interfacial mixing between layers. Since interfacial stability represents a balance between inertial, gravitational, and viscous forces, both the Reynolds number and the densimetric Froude number are important. Keulegan (1949) has proposed a stability parameter, θ.

$$\theta = \frac{1}{(F_2)^2\ Re_2} \qquad \text{VII-6}$$

where the subscripts represent values calculated based on depth and flow in layer 2. Critical values have been defined by data from Ippen and Harleman (1952) and Keulegan to be, as reported by Harleman (1961),

Laminar: $\theta_c = \frac{1}{Re_2}$

Turbulent: $\theta_c = 0.18$

For $\theta > \theta_c$, mixing should not occur. The criteria amount to specifying $F_2 > 1.0$ for instability in the laminar case. Harleman and Stolzenbach (1967) discuss work in turbulent flows which show similar trends of little or no mixing for $F_2 < 1$. While a sharp interface is never obtained, a transition zone always existing, Harleman and Stolzenbach state that "An analysis of correction factors for the uniform density assumption shows that for even moderately wide transition zones, the error introduced is small."

Harleman (1969) notes that the four basic equations can be combined into a single equation for the slope of the interface:

$$\frac{dh_2}{dx} = \frac{\frac{f}{8gh_2}\ |u_2|u_2 - \frac{f_i}{8gh_2}\left(\frac{H}{H - h_2}\right)|u_1 - u_2|\ (u_1 - u_2)}{\frac{\Delta\rho}{\rho}\ |F_2^{\ 2} + F_1^{\ 2} - 1|} \qquad \text{VII-7}$$

where $F_1 = u_1/\sqrt{g\left(\frac{\Delta\rho}{\rho}\right) h_1}$

$F_2 = u_2/\sqrt{g\left(\frac{\Delta\rho}{\rho}\right) h_2}$

h_1 = depth, layer 1

h_2 = depth, layer 2

H = total depth

f = friction factor, water-bottom interface

f_i = friction factor, interface between layers

u_1 = velocity, layer 1

u_2 = velocity, layer 2

$\Delta\rho$ = density difference = $\rho_2 - \rho_1$

$\rho = (\rho_1 + \rho_2)/2$

Harleman makes use of this form for further studies of a variety of problems in which the depth of the wedge is of prime concern.

Bata (1957) concerned himself with the length of the wedge and wrote an equivalent equation.

$$\frac{-\frac{1}{F_o^2}\eta^3(1-\eta)^3 - (\eta-1)^3 + C_Q^2\eta^3}{\alpha(1-\eta + C_Q\eta)^2 + (1-\eta)^3}\, d\eta = \frac{f}{8}\, d\left(\frac{x}{H}\right) \qquad \text{VII-8}$$

where

$\eta = \frac{h_2}{H}$

$\alpha = \frac{f_i}{f}$

$C_Q = \frac{q_1}{q_2}$

$F_o = \frac{u_o}{\frac{\Delta\rho}{\rho} g H}$

q_1 = discharge in layer 1

q_2 = discharge in layer 2

3. Boundary Conditions

Given appropriate boundary conditions, either Equation VII-7 or VII-8 can be solved for a particular case. The boundary condition involves definition of a control section at which something is known about the interface. Bata (1957) notes that this implies critical depth, where the interface changes rapidly, or

$$\frac{dh_2}{dx} \to \infty$$

Thus, from Equation VII-8, since the numerator must equal zero, the following is found:

$$-\frac{1}{F_o^2}\eta^3(1-\eta)^3 - (\eta-1)^3 + C_Q^2\eta^3 = 0 \qquad \text{VII-9}$$

Solution of this equation will in general yield two positive roots for η less than one. Which of the two applies is dependent on conditions downstream of the critical section. Figure VII-2, after Harleman and Stolzenbach (1967), illustrates some possible critical sections. For both cases a and b only one critical depth exists. If the bottom wedge is arrested, the bottom friction terms must be dropped from the basic equation, using $F_o^2 = q_1^2/(\frac{\Delta\rho}{\rho} g H^3)$. In all these cases, once the critical depth is determined, Equation VII-9 can be integrated upstream from that point to determine the profile. If the values of C_Q, F_o, f_b or f_i change gradually with x, the solution can be obtained by treating successive reaches of the channel with constant values of the parameters in those reaches.

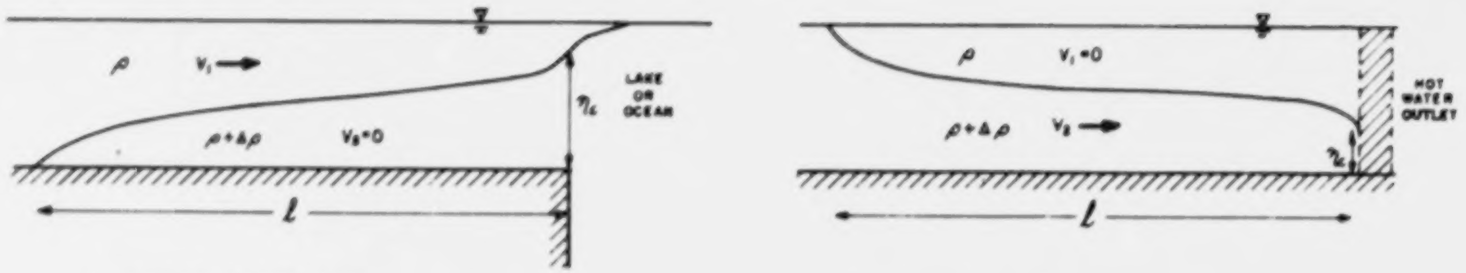
4. Determination of Friction Factors

The foregoing equations require knowledge of friction factors, f, between the bottom layer and the stream bed, and f_i, between the two layers. While such factors are not yet well defined, work by several investigators implies similarity to ordinary open channel relationships. The factor f is determined as usual. A typical means of evaluating f_i was used by TVA (1966). The Reynolds number of the lower layer,

$$Re_2 = \frac{4u_2h_2}{\nu}$$

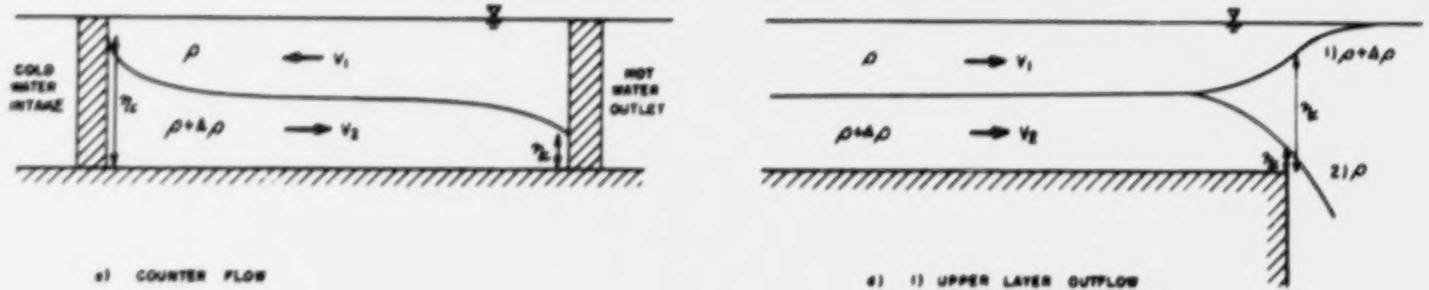
is used with a pipe friction diagram, assuming a hydraulically smooth interface.

Harleman and Stolzenbach (1967) suggest factors B_1 and B_2 to modify the values of the hydraulic radius of the two layers to account


ρ
V_1
$\rho+\Delta\rho$
$V_2=0$
η_c
LAKE OR OCEAN
l
ρ
$V_1=0$
$\rho+\Delta\rho$
V_2
η_c
HOT WATER OUTLET
l

a) ARRESTED BOTTOM WEDGE

b) ARRESTED SURFACE WEDGE


COLD WATER INTAKE
ρ
V_1
$\rho+\Delta\rho$
V_2
η_c
HOT WATER OUTLET
ρ
V_1
$\rho+\Delta\rho$
V_2
η_c
1) $\rho+\Delta\rho$
2) ρ

c) COUNTER FLOW

d) 1) UPPER LAYER OUTFLOW
2) LOWER LAYER DROPOVER

FIGURE VII - 2 CRITICAL SECTIONS IN STRATIFIED FLOW

for two and three dimensional effects, such that:

$$Re_1 = B_1 h_1$$
$$Re_2 = B_2 h_2 \qquad \text{VII-10}$$

where

$$B_1 = \frac{1}{1+2h_1/B}$$

$$B_2 = \frac{1}{2+2h_2/B}$$

B = channel width

5. Solution of the Upstream Warm-Water Wedge Problem

When the upper layer is stagnant ($C_Q = 0$ or $q_1 = 0$), the basic equation can be integrated directly, as by Bata (1957), yielding the following shape of the wedge:

$$f\,\frac{x}{H} = \frac{2}{F_o{}^2}\,(\eta^4 - F_o{}^{8/3}) + \frac{1}{F_o{}^2}\,\frac{8}{3}\,\alpha(\eta^3 - F_o{}^{6/3}) +$$
$$\frac{4\alpha(1+\alpha)}{F_o{}^2}\,(\eta^2 - F_o{}^{4/3}) + \frac{8}{F_o{}^2}\left[\alpha(1+\alpha)^2 - F_o{}^2\right](\eta - F_o{}^{2/3}) \qquad \text{VII-11}$$
$$- \frac{8\alpha}{F_o{}^2}\left[(1+\alpha)^3 - F_o{}^2\right]\left[\ln(1+\alpha-F_o{}^{2/3}) - \ln(1+\alpha-\eta)\right]$$

Setting $\eta = 1$ in this equation enables evaluation of L, the total length of the warm water wedge. Note that a zero wedge length is predicted for $F_o = 1$, while field results indicate F_o about 0.75 is the critical value. Therefore, TVA, in its Browns Ferry studies (1966), adjusted the equation to yield zero wedge length at $F_o = 0.75$. Since h_{2c}/H must equal one when F_o is critical (where $h_{2c} = h_2$ critical) and

$$\frac{h_{2c}}{H} = F_o{}^{2/3}$$

theoretically, TVA suggested use of $kF_o{}^{2/3}$, where $k = 1.21$ will yield the desired condition for $F_o = 0.75$. This was then used to replace F_o

in each of the five places where it appears in parentheses in Equation VII-11. While this certainly accomplishes the goal of adjusting zero wedge length to observed criteria (which was the only interest of TVA), its effect on the exact shape is uncertain. Hopefully, acquisition of good field data will enable evaluation of shape compared to theoretical. In thermal pollution studies, the depth is of importance in defining the portion of the water body which will be affected by the wedge.

6. Wedge into Discharge Channel

A frequent occurrence is the extension of a cold water wedge upstream into the discharge canal. Harleman (1969) observes that allowing such a wedge is a means of minimizing mixing of the condenser water with the receiving fluid. Criteria can be developed to enable choice of more or less mixing. In this case, the average velocity, u_2, of the lower layer is zero, and, therefore, $F_2 = 0$. This is similar to an arrested saline wedge.

The basic equation, VII-7, reveals that F_1, the Froude number in the upper layer in the canal, is less than 1, and continuity in the canal shows that F_o for the canal is less than 1. Harleman (1969) observes that the heated discharge undergoes a rapid expansion at the junction as it spreads laterally and longitudinally in the river. Hence, a critical depth is established in the upper layer at this point, for $F_1 = 1$. This criterion enables evaluation of the upper layer depth at the junction to be

$$h_1 = h_o F_o^{2/3} \qquad \text{VII-13}$$

where h_o = total canal depth

F_o = Froude number in canal upstream of wedge

Presumably, if little mixing occurred, the depth of the heated layer in the main channel would be the same as that at the mouth of the outlet.

As in the river, F_0 controls the formation of a wedge. Theoretically, for F_0 greater than 1, no wedge forms, though this criterion may be subject to revision as before. If it is desired to inhibit mixing, a proper balance must be struck. Too high a Froude number will yield too short a wedge to fully prevent mixing, and too low a value of F_0 will make necessary extremely long discharge canals. More work is needed to define appropriate values for such designs.

7. Other Influences on Wedges

a. Cooling effects - The two layer systems treated thus far have not been subject to heat exchange with the atmosphere. If the wedges are of sufficient length, however, loss of heat from the upper layer to the atmosphere may be significant. Since this cooling increases the density of the upper layer (and hence its Froude number) the length of the wedge is decreased, and the interface position differs from that predicted by a conservative model.

A heat balance requires that the rate of heat transport into the wedge at the discharge point be equal to the rate of heat loss through the total surface area of the wedge. On a differential basis, the decrease in the rate of heat transport at a point must balance the rate of surface heat loss at that point. Harleman and Stolzenbach (1967) have suggested the following formulation:

$$q_t = K_E (T_1 - T_0) \qquad \text{VII-14}$$

where q_t = heat flux out of water body

T_1 = average temperature of upper layer

T_o = air temperature above the flow

K_E = evaporative heat loss coefficient

Writing the one-dimensional equation for conservation of energy yields:

$$u_1 \frac{dT_1}{dx} - \frac{K_E}{\rho c_p h_1} (T_1 - T_o) \qquad \text{VII-15}$$

where ρc_p is the specific heat per volume of water.

Using continuity, and assuming $(K_E/\rho c_p)$ constant, channel width B constant, and $T_1 = T_{10}$ at $x = 0$, the following is obtained by integrating Equation VII-15:

$$\frac{T_{10} - T(x_1)}{T_{10} - T_0} = 1 - \exp\left[\frac{Bx_1}{Q_1} \cdot \frac{K_E}{\rho c_p}\right] \qquad \text{VII-16}$$

where $T(x_1)$ = temperature of upper layer at $x = x_1$. Knowing the temperature at succeeding sections of the wedge enables solution for wedge shape by numerical means.

b. Geometry Effects - The preceding theoretical work has treated a rectangular, prismatic channel. Natural geometric constraints may modify these results. Chikwendu and Francis (1967) experimentally treated the problem of a curved channel, locating their outlet at the midpoint of a circular arc. The channel used was curved through an arc of 135°, with a radius (centerline) of curvature of 60 inches. Operating with densimetric Reynolds numbers (Re_Δ) between 10^3 and 10^4, they found the wedge length (centerline) to be a function of Re_Δ, but indicated the belief that this dependence would vanish for the larger values expected in natural rivers. Their data indicated the following expressions for centerline wedge length.

$$\frac{L}{H} = C\, Re_\Delta^{0.9}\, F_\Delta^{-4} \qquad \text{VII-17}$$

FΔ = Densimetric Froude number

C = constant (1.05-1.10) x 10^{-4}
for curved channel runs

C = (1.95-2.05) x 10^{-4}
for straight channel runs.

It can be seen that the wedge length in the curved channel is only about half that in the straight channel. The helical circulations generated in the curved channel and observed were credited with causing this reduction. The mixing induced may create a less dense surface layer, thereby shortening the wedge.

The wedge was found to be longer on the inner channel wall than on the outer, implying an oblique frontal edge. Additionally, the shape of the wedge was investigated. Results for length were extrapolated to the point of zero length. A Froude number of 0.81 was found for the curved channel and 0.84 for the straight channel as critical values. These compare with Keulegan's (1957) 0.75 as noted earlier. Hopefully, future work will provide more information about geometric effects.

C. Initial Mixing - In considering the temperature of the upper layer some account must be taken of the mixing between the discharge water and the receiving water. As mentioned earlier, the discharge may be designed to minimize this mixing and float the discharge out as a layer. However, if initial mixing does occur, the degree of mixing determines the temperature which will exist in the wedge. This mixing is a function of, among other things, the densimetric Froude number in the channel. The conditions for such discharges, herein called jets, are discussed in the next section. Work is needed to relate such mixing to T_1 in the wedge.

B. Mixing of Heated Waters By Momentum Jets

Heated discharges may enter the receiving water as jets. If the effluent is discharged over a broad area through a system maximizing turbulence at the outflow, temperature gradients in the system will be reduced due to the thorough mixing obtained. If mixing is sufficiently widespread, existing stratification in reservoirs could be destroyed. Among the effects of this destratification is the increased temperature of water taken in for cooling and thus additional water requirements for heat removal. The jet may also develop into a continuous thermal plume, extending from a submerged discharge point. This plume may extend to the surface or, if stratification already exists, it may flow at some point beneath the surface.

To study the effect of the heated jet, it is necessary to describe both the magnitude of temperature produced and the limit of any temperature effects. This essentially means defining the path of the jet, its extent (length, width, and depth), and the distribution of temperatures within the volume of the jet.

1. Physical Factors Involved - Jet diffusion has been studied by numerous investigators. Before reviewing these works, consideration will be given to the physical factors which play a role in the overall problem of heated discharges. Falk (1963), Burdick and Krenkel (1967), and Fan (1967) have all discussed certain of the significant physical variables. The important factors are listed below:

Receiving Water

I. Flow dynamics

- a. Velocity field (magnitudes and gradients)
- b. Ambient turbulence
- c. External influences
  - i. Wind-induced currents
  - ii. Tidal action

II. Channel geometry and characteristics

- a. Shape
- b. Size (widths and depths)
- c. Bottom roughness and configuration (longitudinal and tranverse)
- d. Alignment of channel and shoreline configuration

III. Stratification of receiving water

- a. Due to temperature
- b. Due to solids

Jet Discharge

I. Effluent characteristics

- a. Flow rate (relative to moving stream if discharging to such)
- b. Density difference relative to receiving water
- c. Velocity at outlet

II. Outlet Characteristics

- a. Location
- b. Orientation to receiving water

- c. Submergence
    - i. Bottom effects
    - ii. Free surface effects
- d. Shape of outlet
- e. Size of outlet (width, depth)
- f. Number of outlets and spacing

The engineer has no control (except for choice of location) over the features of the receiving water, but he does control most of the elements of the jet discharge.

2. Jet Mechanisms

Albertson, et al., (1950) and Hinze (1959) recognized and discussed the transition which must occur from the point of jet efflux to a fully developed flow. The velocity discontinuity which exists at the point of efflux creates a region of high shear; the resultant generation of eddies causes lateral mixing, both outward (entrainment) and inward (deceleration of the jet fluid). This initial zone is referred to as the zone of flow establishment and nominally ends at the point where this lateral mixing reaches the jet center line.

When the flow reaches such a fully turbulent stage, it is considered fully established, for the diffusion process is assumed to proceed with no basic change in character. In this range (the zone of established flow) entrainment of surrounding fluid is balanced by deceleration of the entire central portion of the jet. These zones cannot be sharply defined and hence only represent convenient nominal limits.

The work described thus far concerns a free jet. Numerous other factors may play some role in determining the processes of jet action.

Predominant among these are buoyant forces both positive and negative (created by density differences between the jet and receiving fluids), stratification within the receiving fluid itself, currents within the receiving fluid, and the finite physical bounds of the receiving fluid. Wiegel (1964) discusses some of the work done on these added factors, such as jet discharges into a denser fluid, jet discharges into fluids with a density gradient, and horizontal discharge at the water surface.

The discharge of a jet into a denser receiving fluid will result in the jet being deflected upward due to the resulting buoyant force. This buoyant force is much less important than the inertia or momentum flux in the immediate vicinity of the jet efflux, or the zone of flow establishment. Thus the trajectory which the jet describes in a stagnant body of water becomes a function of both the initial momentum flux and buoyancy flux as the flow is decelerated.

The buoyant forces can arise due to any density difference, whether the cause be temperature, salinity, dissolved matter, or whatever. It should also be observed that the problem of a lighter jet rising in a heavier fluid is precisely the same as that of a heavier jet falling in a lighter receiving fluid. The only difference lies in the nature of the limiting boundary: a free surface in the former case and a solid boundary in the latter. Fan and Brooks (1966a) note that they found it more convenient to inject a heavier fluid into the lighter, noting that it makes no difference which way the apparent gravity acts since similarity is according to Froude's law. They also conclude that since friction and wave effects at the free surface are negligible, it can be simulated by the solid bottom of a tank. This is likely true for deeply submerged jets, though added work, such as that by Maxwell and Pazwash (1967), may reveal more significant effects on shallow or surface jets.

Rouse, Yih, and Humphreys, (1952), Schmidt (1957), and Ricou and Spalding (1961) are among those who have investigated plume action with buoyant forces only. Morton (1959), Abraham (1960, 1965), Cederwall (1967), Frankel and Cummings (1965), and Fan and Brooks (1966b) have studied the problem of jets with both initial momentum and buoyancy. Fan (1967) and Wiegel (1964) review the results of several of these works.

If the receiving fluid is not homogeneous, but rather is stratified (has a density gradient), then the jet may or may not reach the water surface. Rawn, Bowerman, and Brooks (1960), Hart (1961), Fan (1967), Abraham (1962), Morton, Taylor, and Turner (1956), and Morton(1959) have all performed work on jet discharge into stratified fluids. Wiegel (1964) describes the three cases which can occur. The jet may reach the surface and there spread out. In a stratified receiving body, Fan (1967) notes that as the rising plume becomes denser and the ambient fluid less dense, the buoyancy force acting on the plume will eventually reverse itself. The plume will then stop rising when the upward momentum vanishes due to the negative buoyancy force. This process leads to the other two cases discussed by Wiegel: a jet which halts beneath the surface and spreads out and a jet which has sufficient momentum to reach the surface and then plunges beneath the surface, where it spreads out as a submerged field.

All the above mentioned phenomena are modified by the existence of currents in the receiving fluid. Studies of non-buoyant jets in cross streams have been made by Gordier (1959), Jordinson (1956), and Keffer and Baines (1963). Buoyant jets have been considered by Csanady (1965), Bosanquet, Horn, and Thring (1961), and Priestley (1956) as well as by Fan (1967), who also discusses the work of Callaghan and Ruggeri (1948) and Vizel and Mostinskii (1965). Zeller (1967) has made field studies in such a case. Abramovich (1963) has summarized several theoretical and experimental studies of non-buoyant jets entering flowing streams at various angles.

3. Dimensional considerations

Dimensional analysis has revealed important parameters for the jet problem, formalizing some of the factors which have been discussed. Jen, Wiegel, and Mobarek (1964) have proposed the following expression, related to earlier work by Rawn, et al. (1960), Frankel and Cummings (1965) and Rawn and Palmer (1929).

$$\frac{T - T_w}{T_o - T_w} = f\left(\frac{x}{d_o}, \frac{y}{d_o}, \frac{z}{d_o}, \frac{\Delta\rho}{\rho_o}, F_D, R_e\right) \qquad \text{VII-18}$$

where T = temperature at specified point

T_w = temperature of receiving fluid

T_o = temperature of jet at $s = 0$

x,y,z = Cartesian spatial coordinates where T is to be evaluated

s = distance from the jet outlet measured along the jet axis

d_o = outlet diameter (or characteristic dimension)

ρ_o = density of jet fluid at $s = 0$

ρ_s = density of receiving fluid

$\Delta\rho = \rho_s - \rho_o$ (sign reversed if effluent more dense)

F_D = densimetric Froude number of jet = $u_o/\sqrt{(\Delta\rho/\rho o)gd_o}$

R_e = Reynolds number of jet = $u_o d_o/\nu$

ν = kinematic viscosity of the jet fluid

g = acceleration due to gravity

u_o = initial jet velocity

Rawn, et al. (1960), have noted that a submerged buoyant jet is a phenomenon involving diffusion and gravity, "...with the Reynolds number characterizing turbulent diffusion and the Froude number the buoyant effect." Hinze (1959), in reviewing several experiments with non-buoyant jets observes a decreasing effect of R_e, becoming negligible above 10^5. Burdick and Krenkel (1967), in reviewing other studies on buoyant systems, note little apparent effect for R_e as low as 2,000 to 4,000. It appears therefore, that the Reynolds number can be neglected as a significant parameter in the jet problem so long as the jet may be considered turbulent, although some question still exists as to the value of the critical Reynolds number.

The dimensional relations presented are of course not all-inclusive as to physical parameters. They were developed for jets into a still, infinite, homogenous receiving fluid. Any of these factors which change could enter into another dimensional equation. For example, Maxwell and Pazwash (1967), studying free surface effects, have included (Z_o/d_o) as an added parameter, where Z_o is the depth of the jet outlet beneath the free surface. Keffer and Baines (1963) and others have proposed a term such as (U_o/U_a) where U_a is the velocity in the ambient fluid, as a parameter for jet discharge into a moving body of water. Thus, an infinite value for this parameter describes the case of discharge into a quiescent body.

Few studies have been done in which channel geometry has been a major consideration.

Two other dimensionless parameters have been developed and deserve some mention. One is the Richardson number, R_i, mentioned by Ellison and Turner (1959), Keffer and Baines (1963), and Zeller (1967). This is merely the inverse of the square of the densimetric Froude number defined in Equation VII-18; however, some have found the Richardson number a more convenient form for their purposes. In oceanography and meteorology it is used almost exclusively. Another parameter, following the notation of Fan (1967), is the spreading ratio, λ, representing the spreading ratio between buoyancy and velocity profiles, since these dissipate at different rates.

4. Analytical Methods of Jet Studies

Only buoyant jets, of prime interest in thermal pollution studies, will be discussed herein. Numerous treatments of jets subject to buoyant forces have been made. The most frequently used basic treatment, the integral approach was introduced by Morton, et al. (1956). Perhaps it would be well to commence by listing certain assumptions basic to any jet analysis and then reviewing other assumptions introduced by Morton. Morton (1961) and Fan (1967) give summaries of these basic assumptions:

a. The fluids are incompressible.

b. Flow is fully turbulent, implying no Reynolds number dependence and that molecular diffusion is negligible compared to turbulent diffusion.

c. Longitudinal diffusion is negligible compared to lateral diffusion.

d. The largest variation of fluid density throughout the flow field is small compared with the reference density. Therefore, the density variation need be considered insofar as it gives rise to buoyant forces and can be neglected in inertial terms. As Fan (1967) notes, this small density variation implies that the conservation of mass flux can be approximated by the conservation of volume flux. The assumption of small density variations is commonly called the Boussinesq assumption.

e. Velocity profiles are similar in consecutive transverse sections of the jet in the zone of established flow. Morton, et al. (1956) added to this the assumption of similar profiles of buoyancy. Work on non-buoyant jets indicated that a Gaussian profile was appropriate. Morton (1961) states that the assumption of similar profiles suppresses all detail of the transverse structure of the jet and that, therefore, any profile shape can be used without loss of additional physical information.

One further assumption made by Morton, et al. (1956) concerns the rate of entrainment across the edge of the plume. It is assumed that the entrainment can be expressed as proportional to the magnitude of the difference between some characteristic velocity in the jet and the velocity of the ambient fluid unaffected by the jet. Morton (1961) notes that, "...if the mutual entrainment is turbulent, the only quantity determining the motion is the relative velocity of the two streams."

Having made all the above assumptions, Morton then applied the basic conservation equations:

(1) conservation of volume flux

(2) conservation of momentum

(3) conservation of density deficiency.

Morton defined an entrainment coefficient, α, and assumed it to be constant as follows:

$$\frac{dQ}{ds} = 2 \pi \alpha u b \qquad \text{VII-19}$$

where u = a local characteristic velocity representing the difference between velocities in the jet and the ambient fluid

b = a local characteristic length

s = axial coordinate of jet

Q = flow quantity

Specification of boundary conditions enables solution of the three equations for the three unknowns: u, ρ, and b. The equations take no account of several physical factors, such as allowing for a current in the ambient fluid. Most treatments considering an added force of this nature have proceeded by modifying Morton's basic approach.

5. Experimental Methods for Jet Study

There are two primary modes of experimental study: field measurements and data from laboratory models. The latter can range from an "infinite" receiving fluid to the development of a physical model corresponding to the complex combination of boundary geometries and flow fields at some specific site.

a. Laboratory modeling for general conditions - Earlier comments have made the point that the phenomenon of a heated jet can be studied by injection of a lighter fluid into a denser receiving fluid or vice versa. The cause of the density difference need not be heat, for the physical flow process is a function of the buoyant forces produced, not the agent producing them. Therefore, numerous techniques are available for study; also, work in such areas as the study of sewage outfalls and resulting plumes become useful. Note, however, that if certain other parameters such as viscosity are dominant in the effects being studied, then the buoyancy-generating agent may be important.

Table VII-1 notes some of the media used by various investigators as well as ranges of physical parameters. The list is obviously not intended to be exhaustive, but rather representative of work done. Descriptions of apparati and techniques for these and similar works may be found in the references.

In general, it is assumed that the values of parameters such as the Reynolds number, Froude number, and current ratio, if the same in the laboratory as in the field, produce results in the laboratory which relate to field conditions. This is also true for such parameters as submergence, studied by Hall and Pazwash (1967). However, certain restrictions are placed on this assumption by the physical impossibility of maintaining complete similitude of both the Froude and Reynolds numbers if water is used in both model and prototype. This difficulty arises because of the very large $\Delta\rho$ required in the model. Hence, laboratory works tend to model Froude considerations and to operate at Reynolds numbers sufficient to insure turbulent flows, which should then eliminate dependence on Reynolds numbers.

b. Modeling for a physical site - In some cases where present

TABLE VII - 1

LABORATORY DATA ON MOMENTUM JETS

Reference	Jet Medium	Receiving Medium	R_e	F_D	$\frac{\Delta\rho}{\rho}$	Studies
Sami, et al (1967)	Air	Still air	220,000	∞	0	Mean axial, radial velocities in zone of flow establishment
Wiegel, et al (1964)	Heated water	Water	700- 9300	5-50	.006- .008	Effect of initial jet velocity and nozzle shape; beach effect
Jen, et al (1964)	Heated water	Water	8300- 21,000	18-180	.003- .010	Temperature distribution in surface jet
Fan (1967)	a) Salt water (heavier than ambient)	a) Linearly stratified salt water	900- 6000	10-130	0- 0.118	Trajectories and half-widths
	b) Salt water	b) Water	6800 +	10-80	.01-.15	Effect of cross stream (U_o/U_a = 4 to 16)
Albertson, et al (1950)	Air	Still air	1500- 10^6	∞	0	Mean jet flow characteristics
Maxwell, Pazwash (1967)	Water	Water	52,000- 177,000	∞	0	Free surface effects; velocity profiles
Bosanquet, et al (1961)	Magnetite slurry (also heated)	Water	——	15-135	0.20- 1.0	Path of jet; varied jet angle
Hart (1961)	Water	Stratified salt water	1700- 18,000	3.2-33.3	0.0271	Height of rise and dilution of subsurface discharge
Frankel, Cumming (1965)	Water	Water + Sugar	——	4-24	0.025	Diffusion efficiency of submerged outfalls

experimental evidence is inapplicable or inadequte it may be necessary to model the geometry and flow conditions expected at a particular site. Ackers (1969) and Silberman and Stefans (1967) have reported work of this type, and Wiegel, et al. (1964) modeled the sloping bottom of a beach. Detailed discussion on modeling techniques is given in Chapter VIII - Modeling of Heated Discharges.

c. Field Studies - Application of the knowledge of jets to field design is a prime goal. Such use required measurements of the phenomenon in the field; however, laboratory measurements have far outnumbered field data. More extensive field observations are needed as theories are advanced which attempt to account for boundary influences, currents, and the like. Such data will aid not only in theoretical development, but will also help to define which parameters are significant.

Zeller (1967) conducted field work on the jet problem and discussed several alternative measurement techniques:

i. Drogues: Gross jet definition - Zeller used drogues to trace the gross streamline pattern in heated jets, enabling determination of direction and a gross measure of velocity. Location of the drogues during the course of a single run was accomplished by stadia or triangulation readings with surveying equipment, with the time of each reading noted. Zeller (1967) found that the use of drogues implies the use of a large enough number (released simultaneously due to the tendency for a jet to meander during the course of a survey) to adequately define the jet, while at the same time being few enough to assure proper tracking. The path of the drogues also serve as a guide to desired locations for other types of measurements of jet features such as velocities, temperatures, and dye concentrations. The use of drogues is cumbersome, and their use for quantitative measurements seems of limited value.

ii. Use of velocity measurements - Current meters may be used to measure velocities within the jet and hence try to define its characteristics and approximate extent. Zeller suggested such a procedure for the initial jet regions, where his drogue studies were inadequate; however, the extensive use of velocity profile measurements can become burdensome and expensive. More important is the fact that velocity fields may not in all cases adequately define the problem since there may be more rapid dissipation of velocity than temperature.

iii. Use of temperature profiles - Use of temperatures to define the extent of a heated jet has been employed successfully both in the lab and in the field. Zeller (1967) used an underwater thermometer for measurements in conjunction with his drogue studies. Although some of his data did not give good definition, this was attributed to data-collection techniques.

iv. Dye studies - Dyes have been used in the laboratory as a visual guide to locate the jet for profile measurements. There seems to be a good case for applying elements of tracer methodology to the study of heated jets. Zeller (1967) made a few attempts to use a fluorescent dye, with concentrations measured by a fluorometer. However, lake depths of less than one meter near the outfall caused much of the dye to become attached to some of the numerous dense patches of vegetation in that vicinity. Hence, results were poor.

Dye injection can be continuous or a slug injection. The former would allow more time for measurements if the flow conditions and hence the jet remained unchanged. Due to the unsteady nature of river currents, the slug injection more nearly yields an instantaneous pattern.

Tracers other than dyes can be used. Harremoes (1966), studying the design of diffusers for sewage disposal in the sea, reported on the use of radioactive tracers to study jet diffusion and dispersion of sewage fields. Studies involved both submerged sewage fields and surface spread of a buoyant sewage field. Abraham (1966), in a discussion of Harremoes' paper, notes the importance of assuring that tracer injection techniques (where no jet outfall already exists) allow a proper accounting of the effect of initial jet mixing.

v. Infrared techniques - Ackers (1969) notes the high cost of extensive data collection by conventional means, and the difficulty in obtaining sufficient data over a short enough time span to adequately represent instantaneous jet conditions. Use of an airborne infrared sensor in an airplane provides a close detail of surface temperatures, and methods exist for conversion of the data into isothermal maps.

Zeller (1967) also discussed infrared surveys, though only one series of six scans was used. The data collected was limited, although a general view of gross jet movement was provided. As instrumentation, techniques, and methods of data reduction improve, infrared techniques may prove important for surface jet studies.

6. Status of Studies

The preceding sections were intended to establish the state of the basic analytical and experimental tools applicable to the momentum jet in thermal pollution problems. The present section will outline results obtained using these tools and indicate directions for needed work.

a. Zone of flow establishment - The definition of the first stages of a jet requires treatment of the zone of flow establishment. For discharge into an essentially quiescent fluid, the results of Albertson, et al. (1960) are frequently used. They show C_2 in Equation VII-20 equal to 0.081, implying that the zone of establishment ends at $6.2d_o$ from the jet discharge, where d_o is the initial jet diameter. Reynolds (1966) has prepared the following tabulation of C_2 values.

$$\frac{x_o}{d_o} = \frac{1}{2C_2} \qquad \text{VII-20}$$

where x_o = limit of zone of establishment

d_o = diameter of circular orifice

C_2 = constant

TABLE VII - 2
EXPERIMENTAL DATA FOR THREE-DIMENSIONAL JETS

Author	Type of Fluid	ρ_s/ρ_o	L/d_o	C_2
Albertson	Air	1	250	0.081
Keagy	Mixed gases	1.03	50	0.086
Becher	Air	1	35	0.077
Forstall	Water	1.01	30	0.078
Taylor	Air	1	30	0.076
Corrsin	Warm Air	~1	25	0.076
Hinze	Warm gases	1	20	0.078
Folsom	Air	~1		0.095
Poreh	Water	~1	10	0.065

Fan (1967) has suggested use of Albertson's value also for inclined buoyant jets, assuming that buoyant forces play a minor role in these early stages of the jet. Based on this assumption, the half-width,

b_o, and the dimensionless concentration, C_o, at the end of flow established can be defined. The solution for the jet in the zone of established flow can then be applied as beginning at these values of b_o and C_o.

Fan (1967) has discussed results obtained by Gordier (1959), Jordinson (1956), and Keffer and Baines (1963) for non-buoyant jets in a cross stream. Fan uses Gordier's data, as shown below, and assumes it also valid for the buoyant case, finding (for a jet issuing 90 degrees to the main flow):

$$\theta_o = 90° - \frac{110°}{k} \qquad \text{VII-21}$$

$$\frac{S_e'}{d_o} = 6.2e^{-3.32/k} \qquad \text{VII-22}$$

Where S_e' = the length of the zone taken along its axis, initial angle θ_o = angle of jet inclination at the end of the zone of establishment, and velocity ratio (u_o/u_a) is expressed as k. Note also that S_e' approaches the 6.2D from Albertson's work for 1/k approaching zero.

Pratt and Baines (1967) have also studied the zone of establishment. For k equal to 3 or 4 (typical values for a discharge canal), S_e'/d is 3 or less. They found that discharges into streams where k approaches 1-2, typical values for a discharge canal, the zone length would approach the order of the discharge width.

Morton (1959), Morton, et al. (1956), and others employed the integral analysis for simple jets and plumes, assuming a constant, α. For a simple jet, the data of Albertson, et al. (1950), indicates $\alpha = 0.057$; the data of Rouse, et al. (1952), yields $\alpha = 0.082$ for simple plumes. The difference in the two α values indicates a difference in entraiment rates for different momentum conditions. The addition of a cross current further complicates matters. These values are based on assumed Gaussian transverse profiles; profiles of another shape would yield another numerical value of α.

The apparent effect of cross streams is to increase the magnitude of the entrainment coefficient. Keffer and Baines (1963) found it to increase along the jet axis, ranging from 0.3 initially to as high as 1.6 at 10 diameters downstream. The values decreased as k increased; this, of course, approaches the case of no ambient current, where α is about 0.082. Keffer and Baines did not use a vector velocity difference. Fan (1967) did use such a difference, and he found values of α between 0.4 and 0.5 for k values from 16 to 2, respectively. These were found by choosing a value which gave best fit to observed profiles; however, another coefficient (a drag coefficient for the pressure difference across the jet) was being simultaneously manipulated to give best fit. Therefore, Fan's values are most indicative when taken as an order of magnitude.

Zeller (1967), studying a jet discharged on the water surface, has also found values of α ranging from 0.496 for $k = 1.75$ to 0.063 for $k = 9.7$, with α decreasing relatively consistently as k increased. The values must be utilized carefully, however, for Zeller's definition differs from virtually all others working with cross streams. Rather than considering a velocity difference, he uses only the jet centerline velocity.

Much of the preceding commentary has centered around a tacit assumption (or approximation) that fluid is equally entrained on all sides of the jet. However, the rate of entrainment through these surfaces may not be equivalent. One example is a free surface, where no entrainment occurs. At the lower surface of a surface jet, shear action tending to entrain fluid is being countered by gravity acting through density differences. It might be expected, therefore, that vertical entrainment would occur in the early reaches of the jet, where shear is sufficient to overcome buoyancy, and then decrease (as the shear decreased) until finally no vertical entrainment occurred. The work of Ellison and Turner (1959), which allowed only vertical entrainment, showed such results. For this case, they formulated α as a function of R_i, the Richardson number, finding $\alpha = 0$ for R_i approximately greater than 0.8. This corresponds to a densimetric Froude number less than about 1.1, indicating that inertial shear has become small compared to buoyant forces. Zeller's (1967) data seems to verify the reduced vertical mixing at later reaches of the jet; however, the initial reaches revealed nothing about such mixing as the jet occupied essentially the entire depth of water for the first several hundred feet from shore.

Jen, et al. (1964) and Wiegel. et al. (1964), have studied surface jets, and their data reveals a very definite vertical entrainment in early stages of the jet, decreasing gradually. Jen found that the bottom of the mixing jet, where initial densimetric Froude numbers varied from 18 - 180, has a slope between 0.125 and 0.182. He noted that the surface jet mixed more laterally than with depth, varying by a factor of about two.

The entrainment coefficient varies, both from side to side and in the axial direction, in lateral mixing. Most studies have neglected such effects and merely used some average, constant α. Sawyer (1963) used an overall α , but he also allowed for differing rates of mixing, α_1 and α_2 on the inside and outside of his two-dimensional jets. Using a sech^2 velocity profile, Sawyer found $\alpha = 0.130$ satisfactory. He found mixing occurred on the outer edge of the jet at twice the rate of the inside edge.

Keffer and Baines (1963), studying a three-dimensional round jet discharged into air, made measurements of mass flux as it varied along the jet axis. He observed the gradient of mass flux and computed values for α showing that it increased along the axis.

Zeller (1967) developed an analytical model of α as α_v, a function of the axial distance, s, and the jet curvature. His field data verifies this variation. Analyses with varying or constant α predicted jet characteristics with negligible differences. While not conclusive, this is an indication that refinement here might well be delayed until other areas have first been strengthened.

Ultimately, the question of boundary effects on the ability of the jet to entrain fluid must be considered. When a jet contacts a channel boundary, entrainment along the surface ceases. At what point does boundary proximity begin to play a role and to what extent?

b. Effects of cross streams - Bosanquet, et al. (1961) studied the path of a jet discharging into an essentially still ambient fluid, providing a theoretical analysis which yielded reasonable agreement with observed paths. However, most instances involve discharge into moving fluids and require somewhat different treatment.

Keffer and Baines (1963) studied jets directed normal to a cross-stream. Their results, as expected, showed more rapid curvature for lower values of k. Keffer and Baines studied a three-dimensional, round turbulent jet not subject to buoyancy; Pratt and Baines (1967) studied the same jet with no buoyant forces present to distances farther from the discharge point.

Fan (1967) considered a round, submerged, buoyant jet, with assumed Gaussian profiles for both velocity and density deficiency. He also noted that a higher pressure can be expected on the upstream edge of the jet than the downstream edge, thus exerting a drag force on the jet plume. Fan derived two equations for conservation of density deficiency and flux of a tracer of concentration C. These equations can be reduced to a more tractable form by using assumed forms of transverse velocity and other profiles. Therefore, if values for the entrainment and drag coefficients can be produced from knowledge of the conditions, a solution for the jet characteristics can be performed. Fan obtained some values for these coefficients by seeking the best fit to experimental trajectories and profiles.

c. Effects of Wind Stresses and Tides - As Zeller (1967) notes, wind stresses may, depending on direction, increase or dissipate the jet's momentum flux. Assuming jet velocity negligible compared to wind velocity, Zeller expressed the wind stress τ_w by:

$$\tau_w = \rho C_w W^2 \qquad \text{VII-23}$$

where W = wind speed

C_w = drag coefficient

ρ = air density.

For Lake Monona, wind stresses were found to usually be quite low. However, stdies by Cornell University (1969) at Cayuga Lake indicate that wind stresses there were of sufficient magnitude to have appreciable effect on movement of surface jets.

The effect of tides on power plants located on tidal estuaries and bays is not well known due to the unsteady nature of the flows. Ackers (1969) reports on several such problems in Great Britian investigated by modeling.

d. Effect of Previously Stratified Fluid - Frequently the receiving water is not homogeneous but rather has vertical density gradients due to solar heating, salt concentrations, or conceivably to other nearby heated discharges. Morton (1961) used an integral method to study vertical discharge into such an environment and Fan (1967) modified this approach to consider varying initial angles of discharge. Both these investigators used a constant α throughout the entire jet flow region. This solution is especially valuable for jets discharged with a strong horizontal momentum, as is expected for most subsurface heated discharges. Using $\alpha = 0.082$, Fan found good agreement with measured jet trajectories and boundaries for these cases. He found three relevant parameters for the problem: the initial jet angle, the jet densimetric Froude number, and a stratification parameter.

e. Effect of Channel Characteristics - The primary interest here centers on geometry effects which cause differences from the infinite body of water usually assumed in analytical developments. Little work has been done on any phase of this, either as it affects jet definition or temperature and velocity profiles. Zeller (1967) made studies in a lake about one meter deep for several hundred feet from the outfall. He found that this inhibited vertical mixing so that one meter jet depth remained approximately constant.

Wiegel, et al. (1964) considered the effect of a sloping beach funning beneath the outfall. Beach slopes of 1:50, 1:100, and 1:200 were used and Jen et al. (1964) found jet bottom slopes from 1:5.5 to 1:8. Therefore, all three beaches interfered with full vertical entrainment. This, of course, limits the thickness of the jet. The width of the jet tends to increase, as all entrainment is lateral. In general, mixing is reduced by introduction of a channel bottom which restricts vertical growth. The exact nature of its effect on width or path, when the ambient fluid is in motion, has not been established; however, Wiegel's work provides insight into understanding the mechanism causing the decrease in mixing due to this effect.

f. Effects of Outlet Characteristics - The initial jet characteristics - width, depth, and velocity - will have considerable influence on the absolute scale of jet path and growth. These effects can be expressed consistently by normalizing the variables by dividing the initial values. However, other factors, such as the shape of the outlet and its orientation, need study.

Albertson, et al. (1950) did initial work on circular versus rectangular, slot outlets; Wiegel, et al. (1964) also studied the effect of shape for a surface jet. However, neither study dealt with a moving ambient fluid. Wiegel's work indicated that rectangular surface jets mix more in the manner of a jet from a circular nozzle than from a two-dimensional slot; however, the efficiency varies with the exact in different parts of the flow cross-section. The part of the dispersing material in the regions of higher velocity is carried ahead of the portions in slower regions. This spreading tendency is somewhat counteracted by lateral and vertical turbulent diffusion of the dispersing material from the faster to slower moving regions. Such diffusion also contributes slightly to the longitudial spreading.

1. The Eddy Diffusion Coefficient

Oceanographers and meteorologists have long used the analogy between diffusion of matter on a microscopic scale and the spread of a tracer material on a macroscopic scale to describe turbulent mixing in the ocean and in the atmosphere. This process can be described by Fick's second law, which is

$$\frac{\partial C}{\partial t} = D_E \frac{\partial^2 C}{\partial x^2} \qquad \text{VII-24}$$

in which C is the concentration, t is the time, x is the distance, and D_E is the eddy or turbulent diffusion coefficient. Although the analogy has been subjected to question, one can find much experimental evidence of the molecular diffusion process on a macro-scale as applied to the spread of tracers in a turbulent field both in the ocean and in the atmosphere. An excellent summary of the process, including experimental verification of the analogy, can be found in a report by Harleman, et al., (1959).

Although equation VII-24 has been used successfully in numerous diffusion investigations, it should be recognized that in the case in question, (that is, in open channel flow), use of this mathematical model may result in erroneous conclusions. The concentration gradient predicted by this model may be in error because of the neglected mass shape.

Orientation of the jet outlet has been treated analytically by Fan (1967) for round, submerged jets. Widths, depths, and paths for various combinations of initial and receiving conditions can be investigated using his results. Similar analytic models are needed for use with surface jets. Studies of sewage outfalls provide some insight into the possible use of a subsurface discharge of heated waters.

C. Dispersion of Heated Discharges

If no initial momentun in the heated discharge exists, the heated effluent will be swept along with the flowing fluid, with dispersion occurring laterally and vertically as a result of both turbulent and convective diffusion. The latter is the movement from one stream tube to another due to concentration gradients existing between the two stream tubes. Such dispersion would also occur downstream from the point of zero velocity difference between the jet and stream. Of course, if the jet covers the entire width of the channel, no further lateral dispersion will occur.

Much work has been done on dispersion and diffusion of substances of the same density as the receiving water; however, little is known concerning these processes when density differences exist. Therefore, a general review of dispersion knowledge will be presented, with the understanding that work is needed to evaluate the various coefficients as found for heated discharges.

The basic dispersion-causing mechanism is the difference in velocity transport due to the convective velocity. Also, the eddy diffusion coefficient as previously defined describes mixing at a point in the flow, and as such may not be the parameter desired to denote mass transfer in a stream section. To predict the mixing characteristics of a river section using equation VII-24, it would be necessary to determine the eddy diffusion coefficient at numerous points and then use an appropriate averaging technique to obtain the overall description of mixing in the section under consideration.

Several procedures are commonly used for determining the eddy diffusion coefficient. Orlob (1959) used the Einstein equation:

$$D_Z = \frac{1}{2} \frac{d(\sigma_Z)^2}{dt} \qquad \text{VII-25}$$

where D_Z is the lateral coefficient of eddy diffusion, t denotes time, and σ_Z represents the standard deviation of the lateral displacement from the mean position of a statistically significant number of eddies. The eddy motion in a turbulent stream, traced by point introduction of particles of polyethelene having a specific gravity slightly less than water, and collecting them in a manner such that statistical analysis of the particle positions could be performed. The particle distribution was then found for several distances downstream from the point of injection and equation VII-25 was utilized to determine the diffusion coefficient. Sayre and Chamberlain (1964) used a similar method.

Pien (1941) determined the lateral and vertical diffusion coefficients using a steady state introduction of tracer material and measuring concentration changes with distance. Both photographic and chemical means were utilized in this investigation and the results demonstrated the variability of the diffusion coefficient with depth. Therefore, one should use the longitudinal mixing coefficient as a measure of turbulent mixing. It should also be noted that the "scale" or mixing length of the diffusion process was found to vary with depth.

Other notable investigations yielding methods for the diffusion coefficient determination include the work of Richardson (1937) who utilized a photometric measuring technique, and Elder (1959) who traced the movement of droplets of permanganate introduced onto the water surface. Both of these investigations utilized the basic equations of diffusion as proposed by Taylor (1953); however, the extremely short length of channel used by Richardson, and the small depths used by Elder may raise some questions as to the applicability of their results.

It should also be noted that the common procedure for determining the eddy diffusion coefficient in the ocean was developed by Munk, et al., (1949) and is given by :

$$k = \frac{\sigma_2^2 - \sigma_1^2}{2(t_2 - t_1)} \qquad \text{VII-26}$$

where k is the horizontal coefficient of eddy diffusivity, and σ_1 and σ_2 are the values of the standard deviation of the tracer concentration along a line perpendicular to the flow at t_1 and t_2, respectively.

The measured widths may be assumed to contain about 95% of the tracer thus allowing the assumption that the measured width, W, equals 4σ. Then:

$$k = \frac{W_2^2 - W_1^2}{32(t_2 - t_1)} \qquad \text{VII-27}$$

Also, the scale of the mixing process is assumed to be:

$$L = \frac{W_1 + W_2}{2} \qquad \text{VII-28}$$

If the physical characteristics of the hydraulic system to be used are known, the vertical diffusion coefficient may also be computed utilizing the formulation:

$$\bar{\epsilon}_y = \frac{\kappa}{6} hu^* = \frac{\kappa}{6} h\sqrt{\frac{\tau_o}{\rho}} = \frac{\kappa}{6} h\sqrt{ghS} \qquad \text{VII-29}$$

where $\bar{\epsilon}_y$ is the average vertical eddy diffusivity, κ is von Karman's constant taken as 0.4, h = depth of the fluid, u^* denotes the shear velocity, τ_o is the boundary shear stress, ρ is the density of water, g represents the gravitational constant, and S is the slope of the energy gradient.

Morris, et al., (1967) determined the lateral and surface diffusivities (D_H and D_S) and the longitudinal mixing coefficient (D_L) under identical flow conditions in experiments. They found that:

$$D_L = 92.7\ D_S \qquad \text{VII-30}$$

and

$$D_H = 0.90\ D_S \qquad \text{VII-31}$$

In the Clinch River below Norris Dam, he found that:

$$D_L = 28.7\ D_S \qquad \text{VII-32}$$

It was concluded that the longitudinal mixing coefficient and the diffusivities are not measures of the same phenomenon; the eddy coefficients being related to turbulent velocity fluctuations and the longitudinal mixing coefficient being a gross measure of the total mixing process and dependent on velocity gradients, dead spaces, channel geometry, etc.

2. The Longitudinal Mixing Coefficient

The continuity equation for the transport of a conservative tracer in a river may be expressed as

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D^{mt}\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D^{mt}\frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(D^{mt}\frac{\partial c}{\partial z}\right) - \frac{\partial (v_x c)}{\partial x} - \frac{\partial (v_y c)}{\partial y} - \frac{\partial (v_z c)}{\partial z} \qquad \text{VII-33}$$

where c equals the tracer concentration; x, y, and z are the coordinate directions with corresponding velocities v_x, v_y, and v_z; and D^{mt} includes the effects of both molecular and turbulent diffusivity and may be a function of x, y, and z (Taylor, 1954). The first term represents the unsteady part of the conservation equation, the next three terms describe mass transfer by convective motion of the fluid.

G. I. Taylor (1954) sought to circumvent the difficulties of solving Equation VII-33 by considering only the cross-sectional average concentration. He used empirical expressions for velocity and the Reynolds analogy to define the variation of v_x and D^m with cross-section. Through heuristic arguments he concluded that the transport mechanisms described by Equation VII-33 could be represented by the following one-dimensional dispersed flow model:

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - \bar{u}\frac{\partial c}{\partial x} \qquad \text{VII-34}$$

where D_L is the longitudinal mixing coefficient and $\bar{u}$ is the average velocity.

Methods of determining the longitudinal mixing coefficient were elucidated in 1962 by Krenkel; however, several new approaches have been utilized since that time. Fischer (1964) has proposed a method based on the change of variance of the concentration-time curve with time, as the tracer cloud moves downstream. The equation for D_L is

$$D_L = \frac{\bar{u}^2(\sigma^2_{t_2} - \sigma^2_{t_1})}{2\Delta t} \qquad \text{VII-35}$$

where $\sigma^2_{t_1}$ and $\sigma^2_{t_2}$ are the variances observed at two stations and Δt is the average residence time between two stations. The variance is calculated from

$$\sigma^2_t = \frac{\sum\limits_i c_i t_i^2}{\sum\limits_i c_i} - \left[\frac{\sum\limits_i c_i t_i}{\sum\limits_i c_i}\right]^2 \qquad \text{VII-36}$$

Harris (1963) considered the mean travel time rather than the variance of the curve in calculating D_L.

$$\int_0^\infty \frac{1}{\sqrt{4\pi D_L t}} e^{-\frac{(x-\bar{u}t)^2}{4D_L t}} dt = \frac{1}{\bar{u}} \qquad \text{VII-37}$$

then

$$g(t) = \frac{\bar{u}}{\sqrt{4\pi D_L t}} e^{-\frac{(x - \bar{u}t)^2}{4D_L t}} \qquad \text{VII-38}$$

satisfies the requirements of a probability density function. Using the method of maximum likelihood, he arrived at the following estimation formular:

$$\hat{\bar{u}} = x\frac{1}{n} \sum_{i=1}^{n} \frac{1}{t_i} = x \text{ (mean value of } \frac{1}{t}) \qquad \text{VII-39}$$

and

$$D_L = \frac{\hat{\bar{u}}(\hat{\bar{u}}\hat{\bar{t}} - x)}{2} \qquad \text{VII-40}$$

where $\hat{\bar{t}}$ represents the mean valuc of t.

Thackston (1966) used an algorithm proposed by Marquardt (1963) for the least squares estimation of nonlinear parameters, implemented by a digital computer program by Baumeister and Marquardt (1962). This program will handle any mathematical model in which a dependent variable can be expressed as a function of a number of independent variables and a number of arbitrary parameters, and will compute the least squares estimates of the parameters based on observed data. The program adjusts the parameters to minimize the residual squared error, ϕ, which is defined as

$$\phi = \sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 \qquad \text{VII-41}$$

where Y_i is the observed value of the dependent variable and $\hat{Y}_i$ is the value estimated by the function.

Either analytic derivatives or derivatives estimated by finite-difference methods may be utilized. Adjustment of any of the parameters may be omitted, their values being fixed or frozen to obtain a constrained minimization of ϕ. The observed and predicted values of Y are both printed and plotted along with nonlinear and support plane confidence limits for all estimated parameters. The program also computes and prints a matrix of correlations between the estimated parameters.

The solution to Equation VII-33 for a rapid introduction of a mass of tracer, M, is

$$\frac{C_i}{\frac{M}{A\bar{u}}} = \sqrt{\frac{Pe}{4\pi t_i T}}\; e^{\frac{-Pe(1 - \frac{t_i}{T})^2}{4\frac{t_i}{T}}} \qquad \text{VII-42}$$

where $M/A\bar{u}$ is the area under the concentration-time curve, T is the mean residence time $(x/\bar{u})$, and Pe is the Peclet Number $(\bar{u}x/D_L)$. Using the observed values of C_i and t_i, the least squares estimates of T and Pe are computed. This form of the equation eliminates the need to use the distance, x, the cross-sectional area, A, or the weight of tracer injected, M, in each least squares fit. Given T and Pe, the values of D_L and $\bar{u}$ are easily computed from the observed distance, x.

In the same article that Taylor (1954) proposed the dispersed flow model, Equation VII-34, he derived the following relation between D_L and the stress at the wall τ_0;

$$D_L = 10.06R \left(\frac{\tau_0}{\rho}\right)^{1/2} \qquad \text{VII-43}$$

where R is the radius of the pipe and π the fluid density. In 1956, Aris developed rigorously the relationship between Equation VII-33 and VII-34. He showed that Equation VII-43 is actually the result of equating the rate of change of the second moments of distributions described by Equations VII-33 and VII-34.

A number of attempts have been made to apply the methods of Taylor and Aris to stream flow. Some investigators attempted to simply use Taylor's expression for D_L directly, calculating τ_0 from the rate of energy expenditure and using a hydraulic radius for R. Such applications are incorrect, since there is no relation between the geometry or velocity distributions in stream flow and those occurring in a pipe. Elder (1959) assumed that only the vertical velocity gradient is important in stream flow, and developed an expression analogous to Taylor's Equation VII-43 but with the coefficient equal to 5.93. Other investigators have derived similar expressions for D_L based upon various assumptions (Thomas, 1958; Parker, 1961; Yotsukura, 1964).

Fischer (1964) compared the predictions of some of the above expressions with the results of experimental laboratory and stream data.

He found a large range in the values of the dispersion coefficient; in general, the values were found to be many times greater than predicted. After a number of possible explanations were considered, he concluded that lateral nonuniformity was the most important. The application of Aris' method to assumed lateral velocity profiles showed that "lateral velocity gradients....can easily overwhelm all other effects in causing longitudinal dispersion." Fischer further showed that the dispersion coefficient is extremely sensitive to the form of the velocity profile, and suggested that successful predictions of D_L may have to be based upon detailed experimental knowledge of the velocity profiles.

As example of the magnitude of the error in the estimation of D_L for natural streams was demonstrated by Thackston (1966). The observed values of D_L were computed by Thackston by the least squares method from the data of Godfrey and Frederick (1963), and were many times larger than the estimated values. The estimated values were based on Elder's (1959) equation, with the constants evaluated in laboratory studies. This equation was tested and verified in field investigations on short, straight, uniform reaches in the Tennessee Valley. The marked disagreement between observed and predicted values of D_L does not mean that the prediction equation is incorrect, but that it was not applicable to the data of Godfrey and Frederick (1963). As previously noted, Fischer (1964) has shown that even very slight lateral velocity profiles can cause much more mixing than the vertical velocity profiles, which is the assumed mixing mechanism in Elder's formulation. It is obvious that such a formulation as Elder's cannot be used to predict mixing coefficients in long reaches of natural streams where lateral velocity profiles and stagnant regions dominate the spread of tracer.

The longitudinal mixing coefficient can also be estimated by using the similarity principle of Kolmogoroff (1941), as shown by Krenkel (1960, 1965) who obtained the following empirical equation from laboratory data

$$D_L = 6.4h^{1.24}E^{0.30} \qquad \text{VII-44}$$

where E is the mean rate of energy dissipation per unit of fluid, which is found from

$$E = hS_e g \qquad \text{VII-45}$$

where S_e is the slope of the energy grade line and g is the acceleration due to gravity.

If the experimental data exactly followed the similarity principle, the exponent of h would be 4/3 and that of E, 1/3. Thackston (1966) derived a form of Equation VII-44, which included a roughness correction and confirmed the functional relationship proposed by Krenkel on both laboratory tests and measurements in several Tennessee Valley Authority rivers under controlled discharge conditions.

It is interesting to note that a similar relationship was derived from data taken from Orlob's (1959) investigations on a four foot wide flume. Again utilizing the depth as a measure of scale, the following regression equation resulted

$$D_S(10^3) = 96.1\ E^{0.504}\ h^{1.19} \qquad \text{VII-46}$$

where D_S is the lateral surface diffusivity as determined by the lateral movement of polyethelene particles on the water surface. Although this equation is based on a different parameter of mixing, D_S, one would expect a similar relationship because of the interdependence of the various mixing coefficients.

3. Prediction of Longitudinal Mixing Coefficient

Thomas (1958) conducted experiments in the Chicago Sanitary and Ship Canal using a point source of Scandium 46 and Tritiated water, and proposed the following equation describing the longitudinal dispersion

$$D_L = \frac{h \bar{u}^3}{u^{*2}} \phi (n) + \frac{h u^{*2}}{\bar{u}} \psi (n) \qquad \text{VII-47}$$

where h is the depth of the flow, u* is the shear velocity, and n is the coefficient in the velocity power law which is assumed to vary from 6 to 10. Thomas gives values for the functions $\phi(n)$ and $\psi(n)$ within the stated range. Using equation VII-47 it was found that the mixing coefficient was about ten times less than that computed by conventional methods. Thomas proposed that the reason for the discrepancy was the wide variation in velocity over the cross section, since the dispersion coefficient is sensitive to changes in velocity distribution.

Patterson and Gloyna (1963) performed longitudinal mixing tests in the Colorado River and in the Pierce Canal using Rhodamine B as a tracer material. An instantaneous tracer injection was made and a recording fluorometer detected the flow through curves. They stated that the longitudinal mixing coefficients in the Colorado River increased with distance from the injection point because of the increasing importance of transverse shear flow mixing with distance. Several transverse mixing coefficients were also measured using tracer releases at midstream. An empirical equation describing the longitudinal mixing coefficient was presented as

$$D_L = 0.8\, e^{0.034\, \bar{u}\sqrt{A}} \qquad \text{VII-48}$$

however, the data were not sufficient to establish a statistically sound basis for the relationship developed. It should also be noted that the tests were performed downstream from a peaking power operation which would create non-steady state flow conditions and thereby raise some question as to the assumptions made in developing the mixing analysis.

An extensive series of tests and analyses were made by Glover (1964) in both laboratory flumes and in rivers. Comparisons of theoretical and test data showed good agreement in the flume tests, but natural streams yielded mixing coefficients from 10 to 50 times larger than the theory predicted. Several different approaches to the development of a mathematical model describing mixing in three dimensions were developed and several lateral and longitudinal mixing coefficients were presented. Although Glover evidently obtained a large number of both lateral and longitudinal mixing coefficients under differing flow conditions and geometries, only slected data were presented. It would be most instructive to compare this data with other flow geometries and calculation methods.

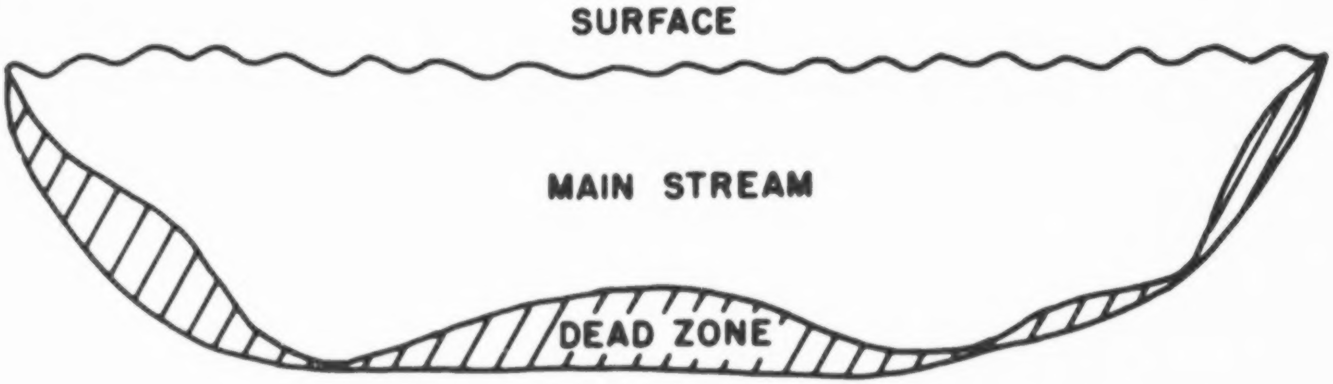
A study by Kisiel (1962) in the Upper Ohio River, using Rhodamine B and a recording fluorometer demonstrated several difficulties encountered when applying the mathematical model describing mixing in a laboratory flume to a river with irregular geometry; however, the data only served to demonstrate that more comprehensive investigations of this type are needed.

The recent work of Parker (1958-63) on the Clinch River under non-steady state and non-uniform flow conditions illustrated the usefulness of the tracer technique in unusual hydraulic studies.

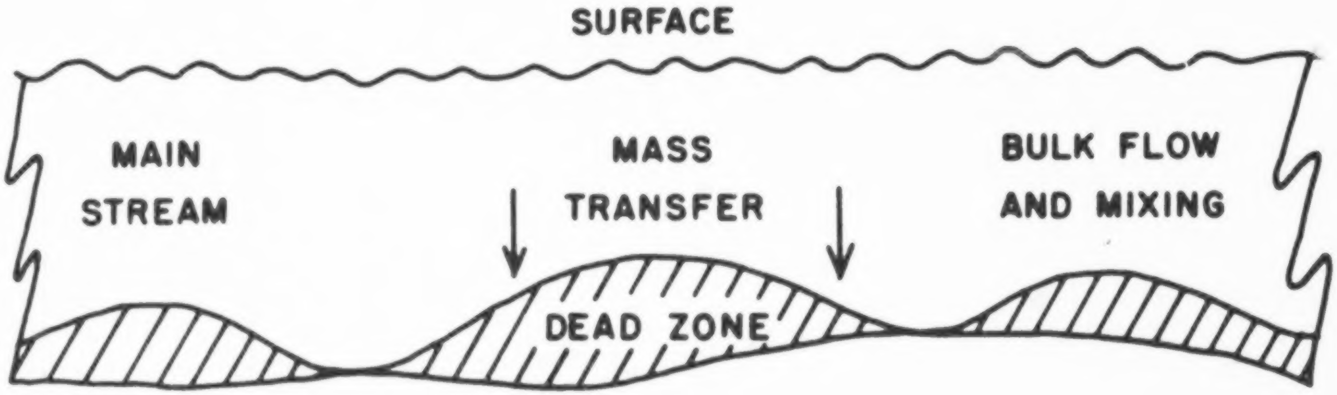
An excellent review of existing knowledge from dye dispersion studies by Diachisin (1963) developed the mathematical models for one, two and three dimensional diffusion, reviewed the methodology for the determination of mixing coefficients, and presented some field data on diffusion coefficients.

Perusal of the literature has demonstrated that although several investigations have yielded information on a particular river under an existing flow condition, the data necessary to predict and understand the diffusion phenomenon are not available. It is obvious that in order to more fully delineate the parameters involved in the overall mixing process in inland waterways, controlled data from field scale measurements are required.

Hays, Krenkel, and Schnelle (1966) proposed that a better description of the spread of material in streams and rivers could be formulated if a typical cross section were considered to consist of two distinct zones: a main stream and a stagnant or dead zone. Figure VII-3 depicts this concept. In the main stream the dominant mass transport mechanisms are longitudinal and lateral turbulent diffusion impressed upon a velocity profile with relatively weak gradients. Thus, many of the effects that cause deviation from the one-dimensional dispersed flow model have been isolated from this zone, and it should be adequately described by such a model. In the dead zone, longitudinal velocity is essentially zero, and lateral mass transport is the only important mechanism. While


SURFACE
MAIN STREAM
DEAD ZONE

CROSS SECTION


SURFACE
MAIN STREAM
MASS TRANSFER
BULK FLOW AND MIXING
DEAD ZONE

LONGITUDINAL SECTION

FIGURE VII - 3 DEAD ZONES IN STREAMS

some longitudinal transport may be present in the dead zone, it is negligible compared to such transport in the main stream. Also, note that the interface between the main stream and dead zone simulates the sharp velocity gradients characteristic of turbulent velocity profiles near the banks of streams and rivers.

It is not clear, at this point, what form the lateral mass transfer mechanism within the dead zone should take; however, it may be satisfactory to assume uniform concentration within a given dead zone cross section. This is tantamount to saying that any dead zone cross section is perfectly mixed. For this description it is appropriate to assume that mass transfer is proportional to the difference in the average concentration in the main stream and the concentration in the dead zone.

However, the perfectly mixed dead zone cross section may be too crude a description. A more sophisticated approach would be to consider that material must diffuse laterally in and out of the dead zone according to the time-varying concentration at the interface. In this case, the geometry of the dead zone must be specified in order to establish the rate at which material is exchanged between the main stream and the dead zone.

Thus, the simultaneous partial differential equations describing concentrations in both the main stream and dead zone can be written

$$\frac{\partial C_a}{\partial t} = D_a \frac{\partial^2 C_a}{\partial x^2} - u \frac{\partial C_a}{\partial x} + K \frac{P}{A_a} (C_d - C_a) \qquad \text{VII-49}$$

$$\frac{\partial C_d}{\partial t} = K \frac{P}{A_d} (C_a - C_d) \qquad \text{VII-50}$$

The conventional mass transfer group is usually written as K_a where a is the ratio of contact or wetted area to the volume of the main stream. It can be seen that

$$a = \frac{PL}{A_a L} = \frac{P}{A_a} \qquad \text{VII-51}$$

where L is the length of the section under consideration. In like manner

$$d = \frac{PL}{A_d L} = \frac{P}{A_d} \qquad \text{VII-52}$$

where d is the ratio of the contact area to the volume of the dead zone. Thus, K_a is the conventional mass transfer group based upon the volume of the main stream, and K_d is the mass transfer group based upon the volume of the dead zone. Equations VII-49 and VII-50 may be written

$$\frac{\partial C_a}{\partial t} = D_a \frac{\partial^2 C_a}{\partial x^2} - u \frac{\partial C_a}{\partial x} + K_a (C_d - C_a) \qquad \text{VII-53}$$

$$\frac{\partial C_d}{\partial t} = K_d (C_a - C_d) \qquad \text{VII-54}$$

Note also that

P = contact length in any cross section

A_a = cross-sectional area of main stream

A_d = cross-sectional area of dead zone

C_a = concentration in main stream

C_d = concentration in dead zone

D_a = dispersion coefficient in main stream

K = mass transfer coefficient

x = longitudinal distance

Application of the dead zone model to both laboratory flume and river investigations prove its applicability. Artificial dead zones were created in the laboratory by using staggered bricks and the field studies were conducted under controlled flow conditions below several TVA dams. Figure VII-4 shows typical results obtained comparing the dispersed flow model and the dead zone model.

Fischer (1966a, 1966b) also examined the dispersed flow model and showed that its validity is established only after an initial period during which convection dominates the dispersion. He noted that for the assumptions of this model to be satisfied, the variation of concentration across the section must be small. He presented the following expression for distance, L, from the point of tracer injection, required for Equation VII-34 to be valid

$$L > 1.8 \frac{\ell^2}{R} \frac{\bar{u}}{U_*} \qquad \text{VII-55}$$

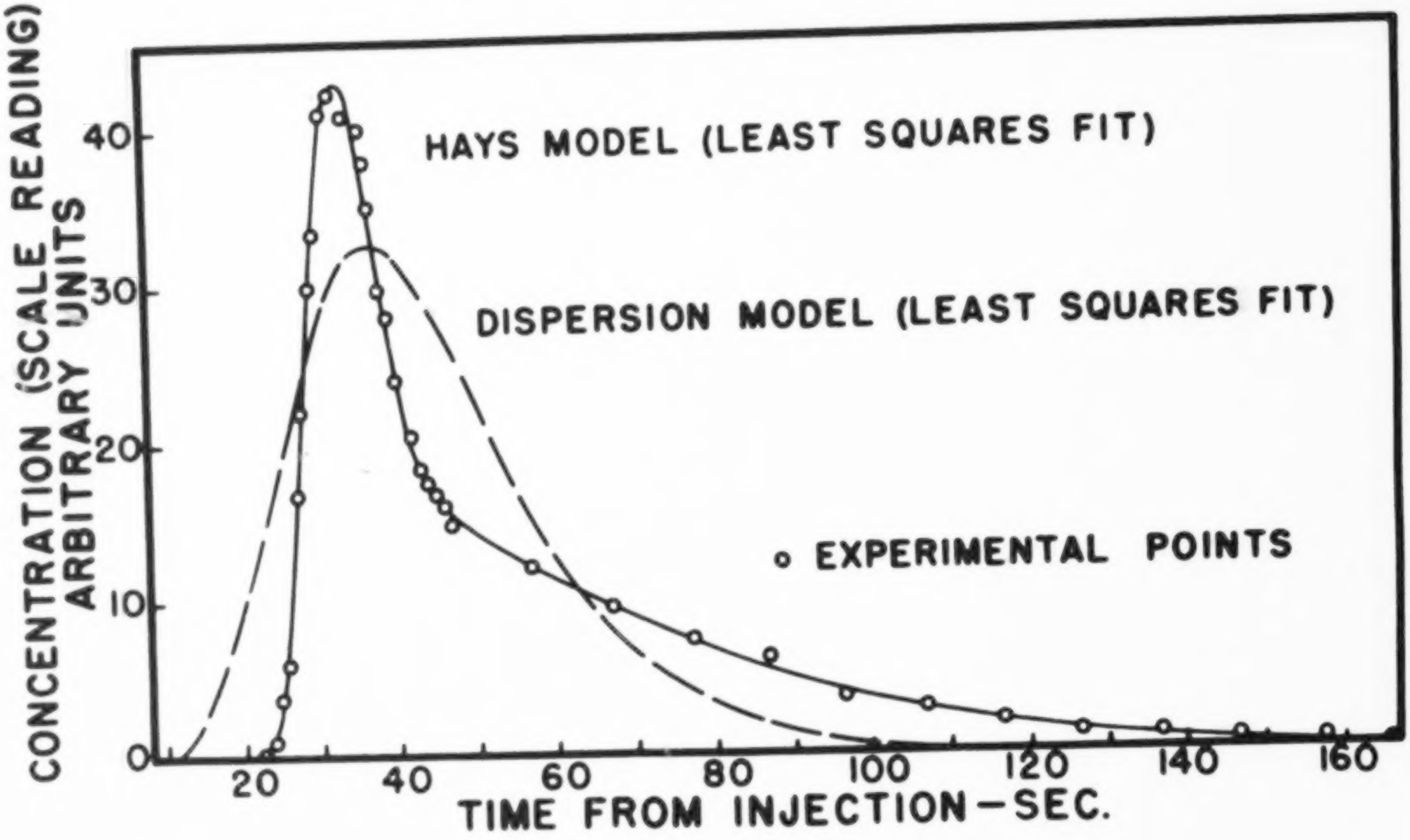


FIGURE VII - 4 COMPARISON OF DISPERSED FLOW MODEL WITH DEAD ZONE MODEL

where ℓ = distance from point of maximum surface velocity to farthest bank.

Fischer (1966b, 1967) also described a method for obtaining dispersion characteristics for a given stream without the need for tracer studies, which are costly. Analysis yielded equation VII-56.

$$D_L = -\frac{1}{A} \int_0^b q'(z)\, dz \int_0^z \frac{1}{D_H\, d(z)}\, dz \int_0^z q'(z)\, dz \qquad \text{VII-56}$$

where

D_H = lateral diffusivity

b = channel width

$d(z)$ = depth at lateral point z

$q'(z) = \int_0^{d(z)} u'(y,z)\,dy$

$u'(y,z)$ = deviation from cross-sectional mean velocity

In a later paper, Fischer (1969) considered the effect of bends and meanders on longitudinal dispersion and transverse mixing. Value of D_H for curving flows were stated to be somewhat higher due to secondary currents induced in a bend. Adapting an earlier analysis, Fischer developed an expression for D_H, showing D_H to be proportional to $\bar{u}^2 d^3 / R_b^2 U_*$, where R_b is the radius of curvature.

Fischer also developed a numerical solution for D_L including the effects of alternating bend directions. It was found that in narrow streams, reasonable results were obtained by considering the flow to be a uniform, infinitely long curve in one direction; in wider streams, it was necessary to consider the alternate directions of the bends.

4. The Vertical Mixing Coefficient

The turbulent diffusion coefficient, or mass transfer coefficient, is often considered to be equal to, or proportional to, the eddy viscosity, or momentum transfer coefficient, ϵ_y. The eddy viscosity, analogous to kinematic viscosity in laminar flow, was defined by Boussinesq to be

$$\tau = \epsilon_y \frac{d(\rho u)}{dy} \qquad \text{VII-57}$$

Where τ = the shear stress, ρ = the density, and u the longitudinal velocity.

Based on Vanoni's modification of the von Karman universal velocity distribution for open channel flow,

$$u = u_{max} + \frac{u_*}{K}\left(1 + \ln \frac{y}{d}\right) \qquad \text{VII-58}$$

where K is the von Karman coefficient, d = the depth of flow, and u_* is the friction velocity $= \sqrt{\frac{\tau_o}{\rho}}$, where τ_o is the shear stress at the channel bottom, the relation

$$\epsilon_y = K u_* y\left(1 - \frac{y}{d}\right) \qquad \text{VII-59}$$

may be derived, expressing ε_y as a function of the fractional depth of flow. Equation VII-59 can also be derived from the Prandtl universal velocity distribution.

In the derivation of Equation VII-58 the shear stress was assumed to be constant throughout the depth. Another form of the von Karman logarithmic velocity distribution can be derived by assuming that the shear stress varies linearly from τ_o at the bottom to zero at the surface. The resulting equation is:

$$u = u_{max} + \frac{u_*}{K} + \left[\sqrt{1 - \frac{y}{d}} + \ln(1 - \sqrt{1 - \frac{y}{d}}) \right] \qquad \text{VII-60}$$

Following the same procedure as in the derivation of Equation VII-59, the following expression is obtained:

$$\varepsilon_y = 2\ Ku_*\ (d-y)\ \ (1 - \sqrt{1 - \frac{y}{d}}) \qquad \text{VII-61}$$

Al-Saffar (1964) measured the vertical mass transfer coefficient, Dy, in open-channel flow and compared it with ε_y as predicted in Equation VII-59. The variation of both with depth was almost exactly the same. He found that the maximum value of Dy was slightly less than the maximum of ε_y, within experimental accuracy.

An expression for the average value of ε_y may be obtained by integrating Equation VII-59 with respect to y and dividing by the total depth. The resulting equation is

$$\overline{\varepsilon y} = \frac{K}{6} du_* \qquad \text{VII-62}$$

If K is assumed to be 0.40, and Ky is assumed to be equal to $\bar{\varepsilon}_y$, as shown by Al-Saffar,

$$\bar{D}_y = 0.067\ du_* \qquad \text{VII-63}$$

In an infinitely wide, rectangular open channel, where shear on the sides does not influence the velocity distribution (two-dimensional flow),

$$u_* = \sqrt{gdS_e} \qquad \text{VII-64}$$

where g = the acceleration of gravity and S_e = the slope of the energy grade line.

No reports have been found describing the actual measurement of D_y in natural streams. However, several values have been obtained in stratified lakes and reservoirs. Hutchinson (1957) reported values of $2\text{x}10^{-3}$ to $4\text{x}10^{-3}$ cm^2/sec for Lake Mendota, and $0.3\text{x}10^{-2}$ cm^2/sec for Linsley Pond. Both sets of values were derived from observing the change in temperature in the hypolimnia of stratified lakes. Values of 1 to $12\text{x}10^{-2}$ cm^2/sec were derived from observing the change in the

HCO_3 concentration in Linsley Pond. Orlob and Selna (1967) presented a mathematical model of thermal stratification, and using observed temperature data from Fontana Reservoir, estimated values of approximately 0.12 cm^2/sec in the hypolimnion. Using the same method Orlob and Selna (1968) reported the following values of D_y(in cm^2/sec):

Fontana Reservoir	0.81 @ surface
	0.17 @ thermocline
	1.15 @ 28.5 m
Hungry Horse Reservoir	3.7 @ surface
	0.12 @ thermocline
	1.7 @ 54 m
Lake Tahoe	9.2 @ surface
	0.1 @ thermocline
	1.2 @ 90 m
Castle Lake	2.6 @ 3 m
	0.02 @ thermocline
	1.5 @ 22 m

Morris and Thackston (1969) measured the vertical mixing coefficients in interflows in Cherokee Lake using fluorescent dye tracers. The interflows occurred above the main thermocline, but in a region with a significant temperature gradient. The average values of D_y in the region of the dye cloud ranged from $2x10^{-2}$ to $8x10^{-2}$ cm^2/sec, approximately the same as those reported by Hutchinson, but much less than those reported by Orlob and Selna. However, there was a sharp decrease in D_y directly below the dye cloud in the more stable region of the thermocline. Values of D_y at the thermocline were essentially zero, as no dye could ever be detected crossing the thermocline.

These data show that "observed" values of D_y in deep or slow-moving stratified environments are quite widely variable, and that no method of prediction is available, as for turbulent flowing streams. However, it does illustrate that D_y is strongly affected by the stability of stratification, and that rates of heat or mass transfer across a thermocline, or in a region of sharp temperature gradient, are much less than in an unstratified environment. For this reason, mathematical models of heat dispersion which use values of D_y calculated from Equation VII-59 or Equation VII-63 are likely to be in great error.

So far as is known, there is no method of estimating what the values of D_y might be in the region between the hot and cold layers in a true stratified flow condition, such as would be encountered in the surface discharge of a heated effluent into a flowing stream. It would certainly be a function of the average hydraulic properties of the stream,of the relative depth of the interface, and of the temperature gradient between the layers. This is an area in which further research definitely is needed.

5. The Lateral Diffusion Coefficient

Vertical temperature stratification is very stable because an eddy momentarily displaced from its vertical position tends to be returned to its original position quickly by the forces of positive or negative bouyancy, without giving up any of its temperature or mass. However, horizontal stratification is not stable, because there is no force of horizontal buoyancy tending to return an eddy to its original position.

The lateral diffusion coefficient is usually measured in a channel by releasing a tracer at a constant rate at a point in the stream and determining its rate of spread by measuring the tracer concentration across several traverses at different distances downstream. The system is analagous to the Eddy Diffusion System mentioned in VII-C 1.

At one time it was thought that the surface diffusion coefficient D_s would be smaller than the later diffusion coefficient D; because D_y at the surface is less than $\bar{D}_y$, but experimental evidence seems to show that they are equal and can be described reasonably well in straight channels by the equation

$$D_z = 0.23\ du_* \qquad \text{VII-65}$$

6. Application to Heated Discharges

Edinger and Polk (1969) have provided solutions for the case of a heated discharge into a river of uniform velocity. The discharge is located along the bank and the efflux is parallel to the streamflow. The assumption is made that the jet does not affect the main stream flow and Equation VII-33 is reduced to the following steady state case:

$$u \frac{\partial c}{\partial x} = \frac{\partial}{\partial z} \left(e_z \frac{\partial c}{\partial z}\right) \qquad \text{VII-66}$$

Two other solutions are presented: the case mentioned above but with surface cooling considered and the case in which vertical (y-direction) mixing is also important.

Two means of describing the data have been used: the fraction of cross-sectional area contained within a given temperature rise contour (as a function of distance from the source) and the surface area contained within a given temperature rise contour. The reader is referred to the report for details. Some of the general analytical findings follow.

1. The surface area varies inversely with the cube of the concentration ratio for the two-dimensional case and the 3/2 power for the three-dimensional case.
2. For a given concentration ratio in the two-dimensional case the area varies with the cube of the plant pumping rate, providing a means for evaluating the effects of plant growth. Area varies with the 3/2 power for the three-dimensional case.
3. For a given concentration ratio, the area varies inversely the square of the river flow in the two-dimensional case.
4. The distance to the fully mixed contour, L_m is

$$L_m = \frac{WQ_R}{\pi D_z d}\left[1 - \left(\frac{Q_P}{Q_R}\right)^2\right] \quad \text{(2 - dimensional)}$$

Q_P = plant flow

Q_R = river flow

W = stream width

d = depth

D_z = vertical dispersion coefficient

D_y = lateral dispersion coefficient

$$L_m = \frac{Q_R}{\pi\sqrt{D_z D_y}} \left(1 - \frac{Q_P}{Q_R}\right) \quad \text{(3 - dimensional)} \qquad \text{VII-68}$$

It will be necessary to more adequately test the theory against field data to determine its usefulness. One question to be answered is how much initial momentum affects the results.

Of course, similar solutions can be developed for other outlet arrangements and orientation, but the turbulent mixing coefficients D_y and D_z need evaluation. These have not yet been defined for heated flows. Therefore, while the model proposed by Edinger and Polk shows promise, additional work is required to determine its validity.

D. Research Needs

1. Wedges

The most obvious need is for field data (and good laboratory data) to test currently existing models and propose modifications. There is little field data available, with its subsequent insight to theoretical limitations. It is, therefore, difficult to define exactly where the next refinements in theory must come. However-obviously work is needed to relate the apparent criterion of critical $F_o = 0.75$ to the theory in a proper manner.

More work is needed to define interfacial shear and friction factors. This may be secondary to other questions presently, but a look at the equations show that errors in f_i are reflected in the final results. Effects of geometry, channel shape, etc., need study although much can be gained first by qualitative review of field data. As mentioned, there is also a need to translate initial mixing of a jet into some average temperature in the upper layer of a jet.

Much remains to be done concerning surface heat exchange and solar heating. If wedges of sufficient length and area are found, data from them will aid in evaluation of existing cooling models. One question not considered yet is the question of pre-existing stratification and its effect on potential wedges and/or surface layers. They may be forced into a layer beneath the surface if the existing surface temperature is greater than that of the condenser discharge. They would then be subject to a water-water interface on both sides, with subsequent modifications in length, etc. Such layers deserve study, for their possibility for dissipation of heat is limited and the volume of water affected by heated water (both by solar heating and heated discharges) is greater.

2. Heated Jets

While some work has been done on length and trajectory of the jet establishment zone, less has been done concerning characteristics of that zone. Sami, et al. (1967) have made a very comprehensive study of velocities, pressures, and turbulence characteristics in this zone for a jet into a still fluid, but more work is needed for flow affected by cross streams.

Another item for study is the non-uniform velocity and temperature in the initial jet section. Such non-uniformity is especially likely to be found in such cases as discharge canals and may result in a shorter zone of establishment. The actual definition of initial jet size and velocity may be difficult, especially when compounded by such features as a cold water wedge intruding up the discharge canal. All present analysis has used an approximation of a uniform velocity across the jet section.

While the present mathematical model of the entrainment phenomenon may not be the ultimate statement, it nontheless is very well related to physical processes and much work has been expended toward its development. The critical parameter appears to be α, the entrainment coefficient. The need exists for adequate definition of this parameter as a function of such parameters as k, the velocity ratio, and the Richardson (or Froude) number. In short, for discharge under given conditions, what entrainment rates are expected? The question of vertical entrainment for a surface jet is another area where entrainment rates need evaluation. The effect of a cross stream on these rates should be investigated.

Entrainment coefficients have been shown to vary axially and laterally. While more work is needed to define these relationships (especially for low velocity ratios), there are indications that reasonable descriptions of jet behavior can be obtained without this refinement and that priority should be given to other effects on jets. Ultimately, the question of boundary effects on the ability of the jet to entrain fluid must be considered. When a jet contacts a channel boundary, entrainment along that surface ceases. At what point does boundary proximity begin to play a role and to what extent?

At the present time (1969), little knowledge seems to exist concerning applicability of any of the theoretical developments to description of field problems under a wide range of conditions. Work is needed to define appropriate drag and entrainment coefficients prior to design use. Much of the work mentioned has involved higher Froude numbers and velocity ratios greater than 4. Data is needed for these cases where the velocity ratio, k, approaches 1, as this is typical of many sites. The lower densimetric Froude numbers (again approaching 1) are also more indicative of heated surface jets and therefore need added work.

Data from both field and laboratory sites are needed for evaluation of theoretical models. Collection of this data, modification of theory on the basis of the results, and preparation of design tools should b e the aim of research on heated jets into both lakes (where k is probably high) as well as rivers (where k could be near or less than 1).

3. Dispersion

The most obvious and pressing needs are for field and laboratory data to verify the use of the diffusion equation and establish values for the mixing coefficients in heated discharges. While considerable work has been done in dispersion, it is not yet known what portions can be translated directly to those cases where density differences exist.

Models such as those proposed by Edinger and Polk should be tested. It may be that a more adequate treatment will require consideration of the initial jet region, with a pure dispersion solution being developed beyond some point of negligible velocity difference.

Further study of cases where surface heat dissipation is important is required. It is possible that the inverse problem, that is heating up of cool waters, may be more tractable in the field.

BIBLIOGRAPHY

Abraham, G., 1966, Discussion of "Tracer Studies on Jet Diffusion and Stratified Dispersion," by P. Harremoes "Advances in Water Pollution Research," Water Pollution Control Federation, Washington, D. C.

Abraham, G., 1965, "Horizontal Jets in Stagnant Fluid of Other Density," Journal of the Hydraulics Division, American Society of Civil Engineers, 91, HYD4, 138-154.

Abraham, G., 1962, Discussion of "Jet Discharge into a Fluid with a Density Gradient," by W. E. Hart, Journal of the Hydraulics Division, American Society of Civil Engineers, 88, HYD2, 195-198.

Abraham, G., 1960, "Jet Diffusion in Liquid of Greater Density," Journal of the Hydraulics Division, American Society of Civil Engineers, 86, HY6 1-15.

Abramovich, G. N., 1963, The Theory of Turbulent Jets, English edition translated by Scripta Technica, MIT Press, Cambridge, Massachusetts.

Ackers, Peter, 1969, "Modeling of Heated Water Discharges," Engineering Aspects of Thermal Pollution, Vanderbilt University Press, pp. 177-212.

Albertson, M. L., Dai, Y. B., Jensen, R. A., and Rouse, H., 1950, "Diffusion of Submerged Jets," Transactions, American Society of Civil Engineers, Vol. 115, pp. 639-664.

Al-Saffar, Adnan Mustafa, 1964, "Eddy Diffusion and Mass Transfer in Open-Channel Flow," thesis presented to the University of California at Berkeley in partial fulfillment for the degree of Doctor of Philosophy.

Aris, R., 1956, "On the Dispersion of a Solute in a Fluid Flowing Through a Tube," Proceedings, Royal Society of London, Vol 235A, p. 67.

Bata, G. L., 1957, "Recirculation of Cooling Water in Rivers and Canals," Journal of the Hydraulics Division, American Society of Civil Engineers, 83, HY3, 1265-1-1265-26.

Baumeister, T., III, and Marquardt, Donald W., 1962, "Least-Squares Estimation of Nonlinear Parameters," Share General Program Library, Share Distribution No. 1428 DFE2135(PA).

Bosanquet, C. H., Horn, G., and Thring, M. W., 1961, "The Effect of Density Differences on the Path of Jets," Proceedings, Royal Society of London, A263, 340-352.

Burdick, John C., III, and Krenkel, P. A., 1967, "Jet Diffusion Under Stratified Flow Conditions," Technical Report No. 11, Sanitary and Water Resources Engineering, Vanderbilt University.

Callaghan, E. E., and Ruggeri, R. S., 1948, "Investigation of the Penetration of an Air Jet Directed Perpendicularly to an Air Stream," NACA TN1615.

Cederwall, K., 1967, "Jet Diffusion: Review of Model Testing and Comparison with Theory," Report Hydraulics Division, Chalmers Institute of Technology, Goteburg, Sweden.

Chikwendu, L. N., and Francis, J. R. D., 1967, "Arrested Warm Water Layers in Curved Rivers," Journal of Institution of Water Engineers, 21, 3, 351-366.

Cornell University, 1969, "Engineering Aspects of Thermal Discharges to a Stratified Lake," College of Engineering, Cornell University, pp. 82.

Csanady, G. T., 1965, "The Buoyant Motion within a Hot Gas Plume in a Horizontal Wind," Journal of Fluid Mechanics, 22, 2, 225-239.

Diachisin, Alex N., 1963, "Waste Disposal in Tidal Waters," Journal of Sanitary Engineering Division, ASCE, 89, SA4.

Edinger, J. E., and Polk, E. M., 1969, "Initial Mixing of Thermal Discharges into a Uniform Current," Technical Report No. 69-1, National Center of Research and Training in the Hydrologic and Hydraulic Aspects of Water Pollution Control, Vanderbilt University, 46 pp.

Elder, J. W., 1959, "The Dispersion of Marked Fluid in Turbulent Shear Flow," Journal of Fluid Mechanics, Vol. 5, Part 4.

Elder, R. A., 1958, "Thermal Density Underflow Design and Experience," Paper presented at Seventh Hydraulics Conference, Iowa Institute of Hydraulics Research, Iowa City, Iowa.

Ellison, T. H., and Turner, J. S., 1959, "Turbulent Entrainment in Stratified Flow," Journal of Fluid Mechanics, 6, 3, 423-448.

Falk, L. L., 1963, "Waste Dispersion in Receiving Waters," Journal, Water Pollution Control Federation, Vol. 35.

Fan, Loh-Nien, 1967, "Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids," Report No. Kh-R-15, W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology.

Fan, Loh-Nien, and Brooks, N. H., 1966a, Discussion of "Horizontal Jets in Stagnant Fluids of Other Density," by G. Abraham, Journal of the Hydraulics Division, American Society of Civil Engineers, 92, SAL, 296-300.

Fan, Loh-Nien, Brooks, N. H., 1966b, Discussion of "Turbulent Mixing Phenomena of Ocean Outfalls," by R. J. Frankel and J. D. Cummings, Journal of the Sanitary Engineering Division, American Society of Civil Engineers, 92, SAL, 296-300.

Federal Water Pollution Control Administration, 1968, *Industrial Waste Guide on Thermal Pollution*, Pacific Northwest Water Laboratory, Corvallis, Oregon, 112 pp.

Fischer, H. B., 1969, "The Effects of Bends on Dispersion in Streams," *Water Resources Research*, Vol. 5, No. 2, pp. 496-506.

Fischer, H. B., 1966a, "A Note on the One-Dimensional Dispersion Model," *Air and Water Pollution*, 443-452.

Fischer, H. B., 1966b, "Longitudinal Dispersion in Laboratory and Natural Streams," Report No. KH-R-12, W. M. Keck Laboratory of Hydraulic and Water Resources, California Institute of Technology.

Fischer, H. B., 1967, "The Mechanics of Dispersion in Natural Streams," *Journal of the Hydraulics Division*, American Society of Civil Engineers, 93, HY6, 187-216.

Fischer, H. B., 1964, "Longitudinal Dispersion by Velocity Gradients in Open Channel Flow," Technical Memorandum 64-4, W. M. Keck Laboratory and Water Resources, California Institute of Technology.

Frankel, R. J., and Cumming, J. D., 1965, "Turbulent Mixing Phenomena of Ocean Outfalls," *Journal of the Sanitary Engineering Division*, American Society of Civil Engineers, 91, SA2, 33-59.

Glover, Robert E., 1964, "Dispersion of Dissolved or Suspended Materials in Flowing Streams," *Geological Survey Professional Paper No. 433-B*, U. S. Government Printing Office, Washington, D. C.

Godfrey, Richard G., and Frederick, Bernard J., 1963, "Dispersion in Natural Streams," Open-File Reports, USGS, Washington, D. C.

Gordier, R. L., 1959, "Studies on Fluid Jets Discharging Normally into Moving Liquid," St. Anthony Falls Hyd. Lab. Technical Paper 28, Series B, University of Minnesota.

Harleman, D. R. F., Jordaan, J. M., Jr., and Lin, J. D., 1959, "The Diffusion of Two Fluids of Different Density in a Homogeneous Turbulent Field," Technical Report No. 31, Hydrodynamics Laboratory, Massachusetts Institute of Technology.

Harleman, D. R. F., 1969, "Mechanics of Condenser Water Discharge from Thermal Power Plants," *Engineering Aspects of Thermal Pollution*, Vanderbilt University Press, 144.

Harleman, D. R. F., 1961, "Stratified Flow," *Handbook of Fluid Dynamics*, Section 26, McGraw-Hill.

Harleman, D. R. F., and Stolzenbach, K. D., 1967, "A Model Study of Thermal Stratification Produced by Condenser Water Discharge," prepared for the Wisconsin Electric Power Company, Report No. 107, 51 pp.

Harleman, D. R. F., Hall, L. C., and Curtis, T. G., 1968, "Thermal Diffusion of Condenser Water in a River during Steady and Unsteady Flows (with application to the T.V.A. Browns Ferry Nuclear Power Plant)," Report No. 111, Hydrodynamics Laboratory, Massachusetts Institute of Technology, 79.

Harleman, D. R. F., and Garrison, J. M., 1962, "The Effect of Intake Design on Condenser Water Recirculation," Massachusetts Institute of Technology Hydrodynamics Laboratory Technical Report No. 56.

Harleman, D. R. F., and Elder, R. A., 1965, "Withdrawal from Two Layer Stratified Flow," Journal of the Hydraulics Division, American Society of Civil Engineers, 91.

Harremoes, P., 1966, "Tracer Studies on Jet Diffusion and Stratified Dispersion," Paper presented at Third International Conference on Water Pollution Research, Munich, Germany.

Harris, E. K., 1963, "A New Statistical Approach to the One-Dimensional Diffusion Model," International Journal of Air and Water Pollution, Vol. 7, p. 799.

Hart, W. E., 1961, "Jet Discharge into a Fluid with a Density Gradient," Journal of the Hydraulics Division, American Society of Civil Engineers, 87, HY6, 171-200.

Hays, J. R., Krenkel, P. A., and Schnelle, K. B., Jr., 1966, "Mass Transport Mechanisms in Open-Channel Flow," Technical Report No. 8, Sanitary and Water Resources Engineering, Vanderbilt University.

Hinze, J. O., 1959, Turbulence, McGraw-Hill Book Company, Inc., New York, 586 pp.

Hutchinson, G. E., 1957, A Treatise on Limnology, Vol. 1, John Wiley & Sons, Inc., New York, 1015 pp.

Ippen, A. T., and Harleman, D. R. F., 1952, "Steady-State Characteristics of Subsurface Flow," National Bureau of Standards Circular 521, pp. 79-93.

Jen, Y., Wiegel, R. L., and Mobarek, I., 1964, "Surface Discharge of Horizontal Warm Water Jet," Institute of Engineering Research Technical Report HEL-3-3, University of California at Berkeley, California.

Jordinson, R., 1956, "Flow in a Jet Directed Normal to the Wind," Aeronautical Research Council Report and Memo No. 3074.

Keffer, J. F., and Baines, W. D., 1963, "The Round Turbulent Jet in a Cross-Wind," Journal of Fluid Mechanics, 15, 4, 481-496.

Keulegan, G. H., 1949, "Interfacial Instability and Mixing in Stratified Flows," National Bureau of Standards Research, Paper 2040.

Keulegan, G. H., 1957, "Eleventh Progress Report on Model Laws for Density Currents; Form Characteristics of Arrested Saline Wedges," U. S. Department of Commerce, National Bureau of Standards, Report 5482.

Kisiel, C. C. et al, 1962, "Tracer Studies with Rhodamine B in a 2 Mile Stretch of the Upper Ohio River," presented at XV International Congress on Limnology, Madison, Wisconsin.

Kolmogoroff, A. N., 1941, "The Local Structure of Turbulence in Incompressible Fluids for Very Large Reynold Numbers," Comptes Rendus (Doklady) de L'Academie des Sciences de L'IRSS, Vol. 30, p. 301.

Krenkel, P. A., 1965, Discussion of "The Significance of Longitudinal Dispersion in the Analysis of Estuaries," Advances in Water Pollution Research, Vol. 1, New York, Pergamon Press.

Krenkel, P. A., 1962, "Waste Dispersion Characteristics of Streams Using Turbulent Diffusion Phenomenon," Journal of the Water Pollution Control Federation, Vol. 34, No. 12.

Krenkel, P. A., 1960, "Turbulent Diffusion and the Kinetics of Oxygen Absorption," Thesis presented to the University of California in partial fulfillment for the degree of Doctor of Philosophy.

Marquardt, D. W., 1963, "An Algorithm for Least-Squares Estimation of Nonlinear Parameters," Journal of the Society for Industrial and Applied Mathematics.

Maxwell, W. H. C., and Pazwash, H., 1967, "Basic Study of Jet Flow Patterns Related to Stream and Reservoir Behavior," Research Report No. 10, University of Illinois, Water Resources Center, 63 pp.

Morris, J. S., Krenkel, P. A., and Thackston, E. L., 1967, "Investigations on Turbulent Diffusion in Inland Waterways," Technical Report No. 14, Department of Sanitary and Water Resources Engineering, Vanderbilt University.

Morris, Michael W., and Thackston, E. L., 1969, "Tracing Polluted Reservoir Inflows with Fluorescent Dyes," Technical Report No. 21 in Environmental and Water Resources Engineering, Vanderbilt University.

Morton, B. R., 1961, "On a Momentum-Mass Flux Diagram for Turbulent Jets, Plumes, and Wakes," Journal of Fluid Mechanics, 10, 1, 101-112.

Morton, B. R., 1959, "Forced Plumes," Journal of Fluid Mechanics, 5, 1, 151-163.

Morton, B. R., Taylor, G. I., and Turner, J. S., 1956, "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," Proceedings, Royal Society of London, A234, 1196, 1-23.

Munk, W. H., Ewing, G. C., and Revelle, R. R., 1949, "Diffusion in Bikini Lagoon," Trans., Amer. Geophys. Union, 30.

Orlob, G. T., 1959, "Eddy Diffusion in Homogeneous Turbulence," Journal of Hydraulics Division, American Society of Civil Engineers, 85, 75.

Orlob, G. T., and Selna, L. G., 1968, "Mathematical Simulation of Thermal Stratification in Deep Impoundments," Current Research into the Effects of Reservoirs on Water Quality, Proceedings of the Specialty Conference, ASCE, Technical Report No. 17 in Environmental and Water Resources Engineering, Vanderbilt University.

Orlob, G. T., and Selna, L. G., 1967, "Prediction of Thermal Energy Distribution in Deep Reservoirs," Proceedings, 6th Annual Sanitary and Water Resources Engineering Conference, Vanderbilt University, Department of Sanitary and Water Resources Engineering, Technical Report No. 13.

Parker, Frank L., 1961, "Eddy Diffusion in Reservoirs and Pipelines," Journal of the Hydraulics Division, ASCE, Vol. 87, No. HY3, Proc. Paper 2825, pp. 151-171.

Parker, F. L., 1958-1963, Status Reports on the Clinch River Study, edited by R. J. Morton, ORNL-3119, 1961; ORNL 3202, 1962; ORNL-3370, 1962; ORNL 3409, 1963; ORNL-3721, 1965; ORNL-3941, 1966; Oak Ridge National Laboratory.

Patterson, Calvin, C., and Gloyna, E. F., 1965, "Dispersion Measurement in Open Channels," Journal of the Sanitary Engineering Division, ASCE, 91, SA3.

Pien, C. L., 1941, "Investigation of Turbulence and Suspended Material Transportation in Open Channels," Thesis presented to Iowa State University in partial fulfillment for the degree of Doctor of Philosophy.

Pratt, B. D., and Baines, W. D., 1967, "Profiles of the Round Turbulent Jet in a Cross Flow," Journal of the Hydraulics Division, American Society of Civil Engineers, 92, HY6, 53-64.

Priestley, C. H. B., 1956, "A Working Theory of the Bent-Over Plume of Hot Gas," Quarterly Journal of the Royal Meteorological Society, 82, 165-176.

Rawn, A. M., Bowerman, F. R. and Brooks, N. H., 1960, "Diffusers for Disposal of Sewage in Sea Water," Journal of the Sanitary Engineering Division, ASCE, 86, SA2, 65-106.

Rawn, A. M., and Palmer, H. K., 1930, "Pre-determining the Extent of a Sewage Field in Sea Water," Transactions, American Society of Civil Engineers, 94, Paper 1750, 1036-1081.

Reynolds, J. Z., 1966, "Some Water Quality Considerations of Pumped Storage Reservoirs," Thesis presented to the University of Michigan in partial fulfillment of the degree of Doctor of Philosophy.

Richardson, E. G., 1937, "An Experimental Study of Turbulence Diffusion," Proc. Phys. Soc. of London, p. 479.

Ricou, F. P., and Spalding, D. B.,1961, "Measurements of Entrainment by Axisymmetrical Turbulent Jets," Journal of Fluid Mechanics, 11, 21-32.

Rouse, H., Yih, C. S., and Humphreys, H. W., 1952, "Gravitational Convection from a Boundary Source," Tellus, 4, 201-210.

Sami, S., Carmody, T., and Rouse, H., 1967, "Jet Diffusion in the Region of Flow Establishment," Journal of Fluid Mechanics, 27, 2, 231-252.

Sawyer, R. A., 1963, "Two-dimensional Reattaching Jet Flows Including the Effect of Curvature on Entrainment," Journal of Fluid Mechanics, 17, 4, 481-498.

Sayre, W. W., and Chamberlain, A. R., 1964, "Exploratory Laboratory Study of Lateral Turbulent Diffusion at the Surface of an Alluvial Channel," Circular 484, Geological Survey, U. S. Department of the Interior, Washington, D. C.

Schmidt, F. H., 1957, "On the Diffusion of Heated Jets," Tellus, 9, 3, 378-383.

Silberman, E., and Stefan, H. G., 1967, "Modeling the Spread of Heated Water over a Lake Surface," Technical Report, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Taylor, G. I., 1954, "The Dispersion of Matter in Turbulent Flow through a Pipe," Proceedings, Royal Society of London, 223A, 446-468.

Taylor, G. I., 1953, "The Dispersion of Soluble Matter Flowing Slowly through a Tube," Proceedings, Royal Society of London, 219A, 186.

Tennessee Valley Authority, 1966, Brown's Ferry Nuclear Plant Preliminary Intake-Outlet Design Studies, Report No. 63-7, Tennessee Valley Authority, Engineering Laboratory.

Thackston, E. L., 1966, "Longitudinal Mixing and Reaeration in Natural Streams," Thesis presented to Vanderbilt University for partial fulfillment of the degree of Doctor of Philosophy.

Thomas, Ivor E., 1958, "Dispersion in Open Channel Flow," Thesis presented to Northwestern University at Evanston, Illinois, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Vizel, Y. M., and Mostinskii, I. L., 1965, "Deflection of a Jet Injected into a Stream," Journal of Engineering Physics, 8, 2, 160-163, The Faraday Press, translation of Inzhenerno-Fizicheski Zhurnal.

Wiegel, R. L., 1964, *Oceanographical Engineering*, Chapter 16, Prentice-Hall, Inc., New York, 532 pp.

Wiegel, R. L., Mobarek, I., and Jen, Y., 1964, "Discharge of Warm Water Jet over Sloping Bottom," Institute of Engineering Research Technical Report HEL 3-4, University of California at Berkeley, California, November, 60 pp.

Yotsukura, N., and Fiering, M. B., 1964, "Numerical Solution to a Dispersion Solution," *Journal of Hydra. Div.*, ASCE, 90 (HY5), 83-104.

Zeller, R. W., 1967, "Cooling Water Discharge Into Lake Monona," A thesis submitted in partial fulfillment of the requirements for the degree of Philosophy, University of Wisconsin, 287 pp.

CHAPTER VIII – 1

MODELING OF HEATED DISCHARGES

The basic requirements of modeling for homogeneous fluids have been described in numerous texts and articles. The reader is referred to Keulegan (1966) for a description of three methods of deriving model laws, naming them the dynamic, dimensional, and equational methods. Using these methods, Keulegan (1951) has also examined model laws for distorted models of saline wedges.

A. Stages of Stratified Flows

As in any modeling venture, it is not usually possible to adequately model all phenomena simultaneously. Ackers (1969) notes that in the modeling of heated effluents when motion already exists prior to jet discharge the first requirement is to obtain similarity of flow patterns in the receiving fluid. This modeling is ordinarily obtained by equating Froude numbers (not densimetric) in model and prototype. The second step involves recognition of the dominant mode of dispersion. Ackers suggests a division of the main stages of dispersion as follows:

(1) Turbulent entrainment at the efflux jet. Close to the outfall, the inertia of the jet is important while density differences are not.

(2) Buoyant rise of jet, if submerged. The trajectory of the jet is dependent on inertial as well as buoyancy forces, the mixing being due to entrainment by turbulence at the plume boundary.

(3) The convective spread of effluent from such an initial dilution zone over the surface of the receiving water. This process is dependent on the density difference at the origin of the convective spread, e. g.,

from the boil point of a submerged jet. Whether or not mixing will occur at the interface is dependent on the densimetric Froude number.

(4) The mass transport of the effluent by ambient currents, which impose additional velocity vectors on all other stages; these will vary periodically in tidal areas.

(5) Diffusion and dispersion due to the turbulence in the ambient fluid.

(6) Loss of heat by evaporative cooling.

Modeling principles will be discussed with reference to these stages of dispersion.

Both stages (1) and (2) must be operated at a natural scale (horizontal scale equals vertical scale). Vertical distortion of the model would cause loss of similarity with regard to the vertical turbulent mixing occurring. In general, the criterion for modeling is that the densimetric Froude number, F_Δ, be the same in model and prototype.

$$\left[\frac{V}{\sqrt{g\,\frac{\Delta\rho}{\rho}\,d}}\right]_m = \left[\frac{V}{\sqrt{g\,\frac{\Delta\rho}{\rho}\,d}}\right]_p \qquad \text{VIII-1}$$

where m and p imply model and prototype respectively,

v = velocity

ρ = density of the fluid

d = depth of the fluid

or $\lambda_v = \lambda_d^{1/2}\ \lambda_\rho^{1/2}$ VIII-2

where λ_v = velocity scale

λ_d = depth scale (depth here implies jet dimension)

λ_ρ = scale of $\Delta\rho$

For studies of convective spread, stage (3), Barr (1963b) has developed densimetric Froude-Reynolds number for a geometrically similar model to specify equality in model and prototype. Keulegan (1955) called this term the densimetric Reynolds number.

$$F_{\Delta}R = \frac{\left(\frac{\Delta\rho}{\rho} g\right)^{1/2} \ell^{3/2}}{\nu} \qquad \text{VIII-3}$$

(where ℓ = characteristic length

ν = kinematic viscosity)

Barr notes, however, that if turbulent flow is assured in both model and prototype that strict equality of this parameter is not needed. In fact, such models are usually established on the basis of the densimetric Froude law, with a densimetric Reynolds number high enough to provide turbulent conditions which may require vertical distortion of the model.

Harleman and Stolzenbach (1967) did use a distorted model with densimetric Froude number similarity to study a wedge formation. Modeling friction (both bottom and interfacial) was a concern. There is poor knowledge of the interfacial friction factor and it is difficult to simultaneously satisfy equal friction factors. Therefore, the numerator of the expression for interfacial slope was established as a similitude parameter to assure similarity of frictional effects. This can be expressed as:

$$D^{-1} \frac{N_m}{N_p} = 1.0 \qquad \text{VIII-4}$$

where D = distortion of model = λ_d/λ_ℓ

λ_ℓ = length scale

N = numerator

m = model

p = prototype

The expression for N is that of Bata (1957).

Other studies have been made on convective spread, including modeling the rate of advance of the heated water front (Silberman and Stefan, 1967). Hooper and Neale (1958) reported on an early study in the United States. Extensive modeling has been utilized in Great Britain, where tidal variations of flow provide added difficulties. Examples of such work are numerous (Frazer, Barr, and Smith, 1968; Barr, 1958; Ackers, 1969. The extensive work on saline wedges by the National Bureau of Standards (see, for example, Keulegan, 1957) has provided additional information.

The Froude law is used for stage (4) where the ambient currents are superimposed on the jet discharge. These ambient currents can be treated by the standard laws for homogeneous fluids, including the Froude number with the assurance of a Reynolds number sufficient to insure turbulent flow, and altering the roughness to give correct head losses. Barr (1963a) reports experiments showing that in cases where internal movements (density generated) outweigh gravity effects the simple Froude criterion can be relaxed, resulting in possible reductions in horizontal scale or vertical exaggeration (distortion).

The criterion for similarity of friction losses was stated by Ackers (1969) to be

$$\lambda_c = \lambda_v \lambda_\ell^{1/2} \lambda_d^{-1} \qquad \text{VIII-5}$$

where λ_c = scale for Chezy (or other) coefficient

λ_ℓ = scale of plant dimensions

λ_v = velocity scale

λ_d = depth scale

Little has been done on stage (5), diffusion due to ambient turbulence. A natural (undistorted) model must be used to maintain similarity of horizontal and vertical diffusion. It has been noted (Ackers, 1969) that this reduces Equation VIII-5 to

$$\lambda_c = 1 \qquad \text{VIII-6}$$

Hence diffusion coefficients can be selected to assure similitude of turbulent diffusion. Ackers notes that Frazer, et al., (1968) have shown that longitudinal dispersion will be simulated adequately if the energy is dissipated by adjusting model roughness. The case in point involves almost purely longitudinal gradients, and hence the distorted model was adequate.

The loss of heat by cooling (stage 6) could have significant effects on wedge lengths and other features. Hence, similarity may be sought, though practicality often prevents strict similarity. If test durations are sufficiently short, for example, effects of cooling may be slight. However, some check of the possible effects should be made in any event. Driver and Elder (1969) note that for a model operated in a laboratory without a controlled environment, humidity is likely to be greater and wind movement less than for the prototype, both factors reducing evaporative heat loss. Unless the model is out-of-doors and in the same geographical locale as the prototype, incoming radiation will be different. In addition, depth of radiation penetration might be only a small portion of total prototype depth but greater than the entire model depth. To evaluate the influence of all these factors, Driver and Elder suggest conducting tests concurrently with operation of the thermal model to determine the environmental heat exchange coefficient appropriate to the model. After comparison to the prototype, model results (or model scales) can be adjusted if necessary.

Harleman and Stolzenbach (1967) have proposed equality of the following term as the criterion arising from the heat loss equation shown under warm water wedges:

$$\frac{K_e}{\rho C_p} \cdot \frac{BL}{Q_1} \qquad \text{VIII-7}$$

where K_e = evaporation heat exchange coefficient

ρ = mass density of water

C_p = specific heat of water

B = average width of channel

L = length of channel reach

Q_1 = flow in upper layer

Assuming $K_e/\rho C_p$ is the same in both model and prototype, this yields

$$\lambda_\ell = \lambda_d^{3/2} \qquad \text{VIII-8}$$

or

$$D = \lambda_\ell^{-1/3} \qquad \text{VIII-9}$$

$$D = \text{distortion} = \frac{\lambda_d}{\lambda_\ell}$$

Frazer, et al., (1968) have developed the same relation, though they have not chosen equality of heat loss rates; hence,

$$\lambda_{\varepsilon} = \frac{\lambda_{\ell}}{\lambda_{d}^{3/2}} \qquad \text{VIII-10}$$

where λ_{ε} = scale of rates of heat loss.

Harleman and Stolzenbach observe that since they define the distortion, D both from Equations VIII-9 and VIII-4, it would not, in general, be possible to have both similarity of frictional effects and heat loss.

Maggiolo and Spitalnik (1967) have considered models for change of cooling water temperatures with time, as affected by solar radiation. They relate scales for relative humidity, solar radiation, and stored heat to distorted models. They observe that the model distortion shown in Equation VIII-9 results from a unity scale for temperatures and relative humidities, which also assures similitude of stored heat in the water and the heat radiated by the sun. If it is not practical to adopt a unity scale for radiation, a value is chosen based on available equipment. The resultant model is based on a non-unity relative humidity scale using the geometric distortion previously defined. Such a model is deemed adequate for time variance of temperature but not for such problems as local withdrawal features, where stratification is the dominant factor.

There is at least some background available for modeling all the stages of heated water discharges. Some of the processes can be modeled simultaneously, while others cannot. Modeling of stages (1) and (2) can most conveniently be accomplished by initial density differences being the same in model and prototype, or $\lambda\rho$ = 1. Stage (4) is also compatible with this model. In addition, Ackers discusses the exaggeration of the vertical scale in the model to properly study stage (3) and the use of two models to enable study of cases where stages (1), (2), (3), and (4) are all of importance. The second model is a large scale one of the immediate locale of the jet outlet due to difficulties of representing the initial jet mixing in vertically exaggerated models.

B. Distortion in Heated Discharge Models

Distortion in models of homogeneous fluids has been commonplace. Vertical dimensions are increased because the effects of viscosity and surface tension place a limit on the minimum depth. Keulegan (1966) has analytically shown a means for approximately determining this limit. Essentially, if adherence to this minimum scale for horizontal dimensions yields too large a model, then distortion is employed. However, distortion, as mentioned earlier, rules out similarity of vertical and lateral turbulent mixing. Where convective spread is dominant, distortion may in fact be necessary to obtain similarity. For a model using the same fluid and density difference as the prototype, Ackers (1969) showed that the minimum distortion required for convective spread similitude is as follows:

$$D^{5/2} \quad \lambda_\ell^{3/2} \geq \frac{150}{\left[\frac{\sqrt{g^{\Delta\rho/\rho}}\, d^{5/2}}{L\nu}\right]_p} \qquad \text{VIII-11}$$

where L = distance over which spreading occurs.

However, lesser distortions are acceptable if the error involved in convective spread to some critical position is small. This can be checked by use of congruency diagrams, as recommended by Barr (1959). Barr has suggested one first consider the limits of spread of the heated discharge. If the spread is not adequately simulated, then other elements will not display similarity. He showed that, for $\Delta\rho_m = \Delta\rho_p$, a small natural model could not yield similarity of limits of spread. The best degree of distortion is determined by using congruency diagrams for simpler modes of flow involving density spread, for example lock exchange flow. This is the flow which occurs when a gate (as a lock gate) separating fluids of different densities is lifted. The model distortion of a simplified and verified case is then employed for the prototype case of interest, with some hope of similitude in the more complicated but related case. Choice of distortion is thus removed from the arbitrary category, though more work is needed to establish the limits of the proposed method. Examples of application of the lock exchange relations are given by Frazer, et al., (1968), Barr (1963a), and Ackers (1969). Fairly complete congruency diagrams are given by Frazer, et al., (1968) for both underflow and overflow conditions. The overflow diagram is shown on Figure VIII-1. The following steps outline one means of obtaining the required distortion.

1. Choose the significant length of spread, L, depth, H, and density difference, $\Delta\rho$, for the prototype case.

2. Compute L/H and the densimetric Froude-Reynolds number for the prototype.

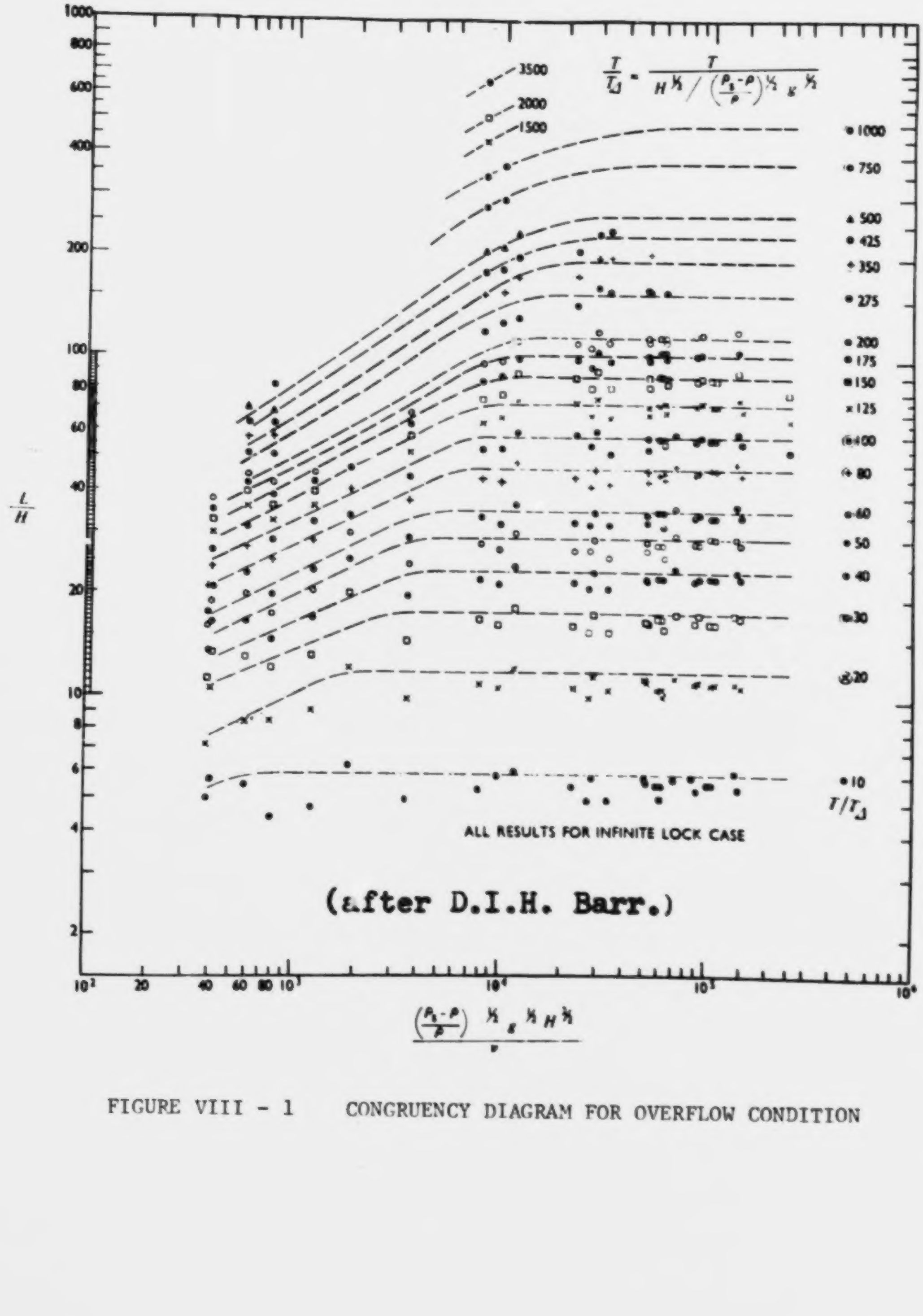


FIGURE VIII - 1 CONGRUENCY DIAGRAM FOR OVERFLOW CONDITION

3. Enter the graph to find $(T/T_\Delta)_p$.

4. Choose the horizontal scale for the model, λ_ℓ.

5. Use the following relations, and, by trial and error, determine the distortion, D.

$$(L/H)_m = \frac{(L/H)_p}{D}$$

$$(T/T_\Delta)_m = \frac{(T/T_\Delta)_p}{D}$$

$$(\overline{F_\Delta R})_m = \frac{(\overline{F_\Delta R})_p}{(\lambda_\ell/D)^{3/2}}$$

The final test of any method for determining model distortion lies in the ability of the model to simulate the prototype. Hopefully, more useful prototype data will be available in the near future, enabling evaluation of many modeling practices.

It should also be noted that the model need not encompass the total body of water, but merely that portion where the heated discharge has an effect. For example, Allen and Allen (1958) used a model representing 1/7 the width of the prototype river inasmuch as dye studies in the existing cooling water discharge had revealed that this modification would not affect the expected flow.

C. Physical Requirements of Models

Generally, a density scale of unity has been used for convenience. Keulegan (1957) demonstrates that the density scale must be unity in a distorted model of saline wedges if the Froude law establishes river discharges. If $\Delta\rho_m$ is chosen greater than $\Delta\rho_p$, Barr (1963a) states there must be a corresponding change of the surface slope (natural or distorted) directly proportional to the increase of $\Delta\rho_m$ to simulate mixing of stratified flows. This is equivalent to a variation from the Froudian law.

One should strive to use a unity density scale. If it is not possible to use heated water, one might use salt water as the receiving fluid. Heated water models do have a more well-defined and stable interface than do salt models (Driver and Elder, 1969). This may especially be true if very large temperature differences exist in the prototype or test durations are long, both resulting in high heat loss. For smaller temperature rises (and lower density differences) salt is more difficult to employ due to measurement limitations. Driver and Elder (1969) have also observed that conductivity measurements involve more effort and expense than temperature measurements and that salt water may increase corrosion. The choice of media must in the end rely on the need to simulate heat losses.

Ackers (1969) has observed the large heat requirement of large scale models. Twelve hours of heating with immersion heaters permitted only one hour of testing. Hence, the model program must be carefully planned, automatic data collection being most useful. Ackers described the control devices and instrumentation used at the Wallingford labs in Great Britain. The possibility of using infrared scanning techniques to provide more rapid collection of surface isotherm data is also suggested.

D. Research Needs for Modeling

The most vital need is for collection of prototype data for comparison with model results. This is the best way to evaluate the effect of model distortion, ways of determining distortion, modeling of heat losses, and the like. Occasionally, model tests are run on problems where the power facility already exists. Then model results can be compared with field observations taken prior to model testing. Allen and Allen (1958) report such an instance, with good agreement obtained. However, more frequently, the facility is in planning stages while model tests occur, and several years may elapse before prototype data is available. In numerous instances, no provision is made for even securing such follow-up data. Hopefully, future field data will strengthen modeling as a valuable tool in studying heated discharges. While analytic techniques will undoubtedly be proposed for treatment of geometry effects and other constraints, models will continue to play an important role for some time, especially in regions subject to tidal action and irregular geometry.

Work is needed to better define the selection of model distortion, enabling increasing confidence in similitude for the phenomena being studied. Possible changes in the geometric distortion might also prove advisable for those cases where climatic conditions and subsequent heat exchange can not be modeled exactly. In those cases where climate is not modeled, means for modification of subsequent results should be investigated.

Use of two models has been suggested for cases where both initial vertical mixing and convective spread are important. Evaluation of the effect of vertical distortion on modeling of this vertical mixing might offer guidelines for possible use of a single model in instances of moderate initial mixing.

Development of laboratory usage of such techniques as infrared scanning may enable more efficient data collection. Reducing the time of data collection attacks the major practical problem in modeling by use of heat, that being the inability to obtain sufficient quantities of heated water to enable lengthy, continuous tests. Development of means for handling this problem in a simple, economical way would likely encourage more frequent use of modeling as an effective tool for studying thermal problems.

BIBLIOGRAPHY

Ackers, P., 1969, "Modeling of Heated Water Discharges." in Engineering Aspects of Thermal Pollution, Ed. Parker, F. L.,and Krenkel. P. A., Vanderbilt University Press.

Allen, J., and J. Allen, 1958, Discussion of "A Hydraulic Model Study of Heat Dissipation at Kincardine Power Station", by D.I.H. Barr, Proceedings Institution Civil Engineers.

Barr, D.I.H., 1963a, "Model Simulation of Vertical Mixing in Stratified Flowing Water". The Engineer, 215, 345-352.

Barr, D.I.H., 1963b, "Model Simulation of Salinity Intrusion in Tidal Estuaries". The Engineer, 216, 885-893.

Barr, D.I.H., 1959, "Some Observations of Small Scale Thermal Density Currents". Proceedings Eighth Congress of International Association for Hydraulic Research, Montreal, 2, Paper 6-C.

Barr, D.I.H., 1958, "A Hydraulic Model Study of Heat Dissipation at Kincardine Power Station". Proceedings Institution Civil Engineers, 10, pp. 305-320.

Bata, G., 1957, "Recirculation of Cooling Water in Rivers and Canals". Proceedings of the American Society of Civil Engineers, 83, H43, Paper 1265.

Driver, E. E., and R. A. Elder, 1969, Discussion of "Modeling Heated Discharges" by Peter Ackers. Engineering Aspects of Thermal Pollution, Ed. Parker, F. L., and P. A. Krenkel, Vanderbilt University Press.

Frazer, W., D.I.H. Barr and A.A. Smith, 1968, "A Hydraulic Model Study of Heat Dissipation at Longannet Power Station". Proceedings Institution of Civil Engineers, 39, 23-44.

Harleman, D.R.F., and R.D. Stolzenbach, 1967, "A Model Study of Thermal Stratification Produced by Condenser Water Discharge," M.I.T. Hydrodynamics Laboratory, Report No. 107, 55.

Hooper, L. J., and L. C. Neale, 1958, "Use of River Models in Cooling Circulating Water Studies". Proceedings Boston Society of Civil Engineers, 45, 356-365.

Keulegan, G. H., 1966, Estuary and Coastline Hydrodynamics, (A. T. Ippen, Editor), Chapter 11, McGraw Hill.

Keulegan, G. H., 1957, "Eleventh Progress Report on Model Laws for Density Currents; Form Characteristics of Arrested Saline Wedges," U. S. Department of Commerce, National Bureau of Standards, Report 5482.

Keulegan, G. H., 1955, "Interface Mixing in Arrested Saline Wedges," Seventh Progress Report on Model Laws for Density Currents, National Bureau of Standards.

Keulegan, G. H., 1951, "Distorted Models in Density Current Phenomena," Fifth Progress Report on Model Laws for Density Currents, National Bureau of Standards.

Maggiolo, O. J., and J. Spitalnik, 1967, "Considerations on Hydraulic Models to be Employed to Study Recirculation Intake Conditions of Cooling Water in Steam Power Stations". Journal of Hydraulic Research, 5, 2, 189-207.

Silberman, E., and H. G. Stefan, 1967, "Modeling the Spread of Heated Water Over a Lake Surface," Technical Report, St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

CHAPTER IX -1

COOLING PONDS AND RUN OF THE RIVER COOLING

A. Cooling Ponds

Cooling ponds are being increasingly used as a source of circulating water for central steam electric stations when land is available at a reasonable price, because they frequently are the simplest, cheapest, and least water intensive method of water cooling (Cotter and Lotz, 1961). Ponds may be constructed by simply pushing up an earth dike, may be operated for extended periods without makeup water, and may serve as a retention basin. Ponds, unfortunately, also have low heat transfer rates, thereby requiring large surface areas. They concentrate dissolved solids, thereby requiring blowdown, and collect impurities since large surfaces are open to the atmosphere.

Possibly the most comprehensive discussion of heat transfer, movement and ambient conditions in natural lakes and ponds is the chapter in Hutchinson's Limnology (1957) on the thermal properties of lakes. The natural thermal cycles of bodies of water are described and standard definitions presented. The thermal properties of lakes vary with latitude, altitude, and depth of the basin. In the temperate zone, most lakes can be described as dimictic; i.e., are freely circulating twice a year, in spring and autumn and inversely stratified in winter and directly stratified in summer. Lakes over a wide range of latitudes absorb during their complete annual cycle 110,000 to 150,000 BTU/sq. ft./yr. Of this total, 60% to 70% is taken up after the spring over-turn and would, of course, require work to be carried down into the hypolimnion. The absorbed summer dose is about one-half the total radiactive energy reaching the water surface.

Though there are many individual articles describing cooling ponds (Langhaar, 1953; Velz and Gannon, 1960; Lima, 1936; Mandelbrot, 1964; Throne, 1951; Harbeck, 1953; Harbeck, 1964), perhaps the most comprehensive treatment is in Berman's (1961) Evaporative Cooling of Circulating Water. Though based on Russian experience, it appears to be the best collection of data about and analysis of cooling ponds available.

Berman suggested that cooling ponds be used only for heat loads greater than 800,000 BTU/hr. For smaller heat loads, tanks with surface areas of 8500 to 11,000 sq. ft. should be used. Suggested dimensions adopted from regulations of the Heating and Power Board of the Soviet Union for cooling ponds are:

depth greater than 5.0 feet at low level

depth greater than 8.2 feet at normal water level

depth less than 10.0 - 13.0 feet since sirculation
ordinarily does not extend deeper

For very large ponds, 1200-1700 acres, maximum depths are from 50-60 feet. In order to efficiently utilize the total area of the pond, stream guides may be provided.

According to McKelvey and Brooke (1959) earth dikes for cooling ponds may be only 6 to 8 feet high, can be constructed at a low cost, can operate for extended periods of time with no makeup and serve as a holding basin for contaminant detection.

The major disadvantages are the large surface areas required, 1 to 2 acres per megawatt of installed capacity; the possibility of fog, on cold days at distances up to 600 feet downwind from the pond; and the low heat transfer rate across the water surface. Brooke and McKelvey indicate transfer rates of 3½ BTU/hr/sq ft/°F surface water and air. Berman (1961) suggests a value of 75-150 BTU/hr/ft^2. Berman's value seems to be closer to the values generally found in the United States. Langhaar (1953) has prepared a series of nomograms based on an energy budget which makes it possible to compute rapidly the surface required for cooling ponds.

In computing the surface area required, daily atmospheric conditions may be used if the holdup time in the pond is greater than 24 hours. The major factors affecting pond performance are surface air temperature, relative humidity, wind speed, wind fetch, solar radiation, silting of the pond, aquatic growth and erosion. It should be recognized that the determination of the size of the pond is still an art because of the many anomalies (Cotter and Lotz, 1961). Velz (1960) has shown how the variability of atmospheric parameters may be taken into account.

Edinger and Geyer (1965) have analyzed cooling ponds on the basis of their circulation patterns and temperature distribution. Though a number of ponds have been designed by rough rule of thumb, 1 to 2 acres per megawatt of installed capacity, a more sophisticated design would take into account the cold water intake rate, the amount of waste heat, and atmospheric conditions.

An approach to 3 to 4 °F is the lowest practicable amount of cooling in ponds of reasonable size. However, deep cooling ponds can provide water at colder temperatures during the year than can even draft towers in colder climates. Based largely upon the pioneering work of Harbeck (1953), it can be shown that the amount of water lost in cooling ponds to dissipate heat may be less than the amount lost in cooling towers. Though evaporative losses are usually the major losses, radiation and conduction can for the conditions listed dissipate up to 65% of the heat load (Throne, 1951). Since wet cooling towers depend almost exclusively upon evaporation for cooling, it can be seen that the water losses in cooling towers can exceed water losses in cooling ponds. If, however, the ponds utilized are not previously existing ponds, then the normal evaporative losses must be added to the heat induced losses.

Berman (1961) has suggested costs of $2 to $3 or more per cfs of cold water flow. Maine Yankee costs for cooling ponds were estimated to be $300 - $500/cfs of cold water flow. These costs indicate the wide variation in costs for cooling ponds.

Spray systems added to cooling ponds increase the heat loss per unit area but also increase the water losses due to the enhanced evaporation. Spray ponds have many of the characteristics of cooling ponds, however, the heat transfer rate is higher, from 2600-5500 BTU/hr/sq. ft., according to the Russian experience (Berman, 1961), or 4000-10,000 BTU/hr/sq. ft. according to American and English experience (McKelvey and Brooke, 1959). Spray ponds, however, are usually unsuitable for a cooling range greater than 18°F. Spray ponds are also, in general, considered uneconomical for large size plants; as the size of the pond increases, the air passing by the sprays is already saturated so the sprays on the downwind side are not very effective. However, South Carolina Electric and Gas Company has built a 10-acre spray pond in conjunction with a swamp cooling area to dissipate 13°F of heat from 180,000 gallons per minute (Moore, 1968). The capitol cost was $985 per million BTU removed.

B. Run of the River Cooling

Until the present concern about thermal pollution became manifest, the availability of large supplies of cooling water were a prime requirement for large power plant locations. Most plants in the East, Midwest and South used run of the river or pond cooling with the overwhelming proportion utilizing run of the river cooling. During 1965, in the North Atlantic Region (as defined by FWPCA), only 1 plant (100 MW) out of 101 utilized cooling towers; in the Southeast Region, 2 out of 61; in the Great Lake Region, zero out of 54; and, for the country as a whole, 116 out of 514 plants utilized cooling towers (Federal Water Pollution Control Administration, 1968). The plants utilizing towers were previously the smaller plants, less than 400 MW, and primarily in the West.

The situation has drastically changed since then and we now find units of 600 to 1000 MW commonly being ordered and station sizes of 3000 to 4000 MW. For an average condenser rise of 15°F, a fossil fueled plant of 4000 MW would require about 4600 cfs, while a nuclear fueled plant would require about 7000 cfs. To limit the temperature rise to 5 °F., the standard recommended by The National Technical Advisory Committee on Water Quality Criteria, would require 14,000 cfs and 21,000 cfs respectively (Federal Power Commission, 1969). The average annual flow of only a few rivers in this country exceed this value.

Detailed comparison of the cost of run of the river plants with other cooling systems is given in Chapter XII on Comparison of Cooling Methods.

C. Research Required

Though the office of Science and Technology of the Executive Office of the President has detailed the considerations affecting Steam Power Plant Site Selection, it has not provided sufficient guidance on the research required for optimum site selection. The topics discussed below, if studied at all, have only been studied for steady state conditions. Non-steady state solutions and stochastic modeling should be emphasized.

1. Though run-of-the-river cooling has been used extensively, there is still not available satisfactory predictive equations for the thermal mixing zone downstream from a plant. Relatively little field data is yet available against which to check such equations.
2. Equations are available for the upstream wedge case and the downstream uniformly mixed case. Little information or satisfactory equations are available for the stratified flow case with surface discharge and with interflow movement.

3. Particularly lacking is information on the vertical, lateral, and longitudinal diffusion coefficients under stratified conditions. The interfacial friction factors for both stratified and interflow conditions are almost completely missing.

4. The use of stochastic modeling of meteorological parameters upon the heat dissipative properties of streams and cooling ponds should be investigated to determine the range of conditions possible. It would also be useful to have some estimates of the damages caused by such extreme conditions.

5. Though a great deal of information is available on cooling ponds, most of this concerns steady state conditions and the determination of empirical coefficients. A rational solution that would allow the simultaneous satisfaction of the continuity, energy and water balance equations would be most useful.

6. Very little work has been done on the conduction and absorption of heat by the bottom and sidewalls of cooling ponds and rivers. Though in most instances this should be a minor source or sink, for large shallow ponds this may not be the case.

7. A generalized tabulation on cooling rates and sizes of cooling ponds required for each section of the country and for each season of the year would be extremely useful to State and Federal administrators.

BIBLIOGRAPHY

Berman, L. D., 1961, "Evaporative Cooling of Circulating Water". Pergamon Press.

Cotter, T.J., and Lotz, R. W., 1961, "Cooling Pond Design in the Southwest". Journal of the Power Division, ASCE, 87, 85-103.

Edinger, J. E., and Geyer, J. C., 1965, "Heat Exchange in the Environment". Cooling Water studies for Edison Electric Institute, Johns Hopkins University.

Federal Water Pollution Control Administration, 1968, Department of the Interior, "The Cost of Clean Water". Vol. II, Detailed analysis, 127, U. S. Government Printing Office, Washington, D. C.

Federal Power Commission, 1969, "Problems in Disposal of Waste Heat from Steam-Electric Plants U. S. Government.

Harbeck, G. E., Jr., 1953, "The Use of Reservoirs and Lakes for the Dissipation of Heat". U. S. Geological Survey, Circular No. 282, U. S. Government Printing Office, Washington, D. C.

Harbeck, G. E., Jr., 1964, "Estimating Forced Evaporation From Cooling Ponds." Journal Power Division America Society of Civil Engineers, 90, 1-9.

Hutchinson, G. Evelyn, 1957, "The Thermal Properties of Lakes". A Treatise on Limnology, John Wiley & Sons, Inc., and Chapman & Hall, Ltd.

Langhaar, J. W., 1953, "Cooling Pond May Answer Your Water-Cooling Problems". Chemical Engineering, 60, 194-8.

Lima, D. O., 1936, "Pond Cooling By Surface Evaporation". Power, 80, 142-144.

Mandelbrot, L., 1964, "The Cooling of Steam Plant Condensers". Translated from the "Bulletin due Centre de Recherches et D'Essais de Chatou," 7, 1-82.

McKelvey, K. K., and Brooke, M., 1959, "The Industrial Cooling Tower". Elsevier Amsterdam.

Moore, W. E., 1968, "Spray Pond Keeps River Within 5F Rise Limit". Electrical World, April, 33-35.

Throne, R. F., 1951, "How to Predict Lake Cooling Action,"Power, 86-89.

Velz, C. J., and Gannon, J. J., 1960, "Forecasting Heat Loss in Ponds and Streams,"Journal, Water Pollution Control Federation, 32, April, 392.

CHAPTER X –1

COOLING TOWERS

A. Major Sources of Information

Though a wide variety of and large number of articles have been published on devices for cooling condenser water, the two best and most detailed technical references in the English language are "The Industrial Cooling Tower" by K. K. McKelvey and Maxey Brooke (Elsevier, 1959), and "Evaporative Cooling of Circulating Water" by L. D. Berman, which is a 1961 translation by Raymond Hardbottle for Pergamon Press of the Russian book published in 1956. Though quite different in its outlook, one should also note the excellent study "Water Demand for Steam Electric Generation", (1965, Resources for the Future, by Paul H. Cootner and George O. G. Lof). For a basic understanding of the integrated concept of electric power generation at an individual station comprising boilers, generators, condensers, and cooling tower and their effects on efficiency and costs it is unsurpassed. What the book does not do is to compare alternate systems at alternate sites. While run of the river cooling water may,in general, be cheaper than cooling towers, if the run of the river plant is not at the load center or at the fuel source, the integrated cost for delivered power may be less for a plant with a cooling tower at the load center or mine than run of the river plant at some more distant location.

For a basic understanding of two workings of a central electric power generating station "Power Station Engineering and Economy" by Bernhardt G. A. Skrotski and William A. Vopat (1960), for more detailed examination of the generation and production of steam from fossil fuels the in-house publication by the Babcock and Wilcox Company -"Steam - Its Generation and Use" (1963) is recommended.

Also useful as reference works are the house publications of the major manufacturers of cooling equipment and the Cooling Tower Institute. Representative publications include: "Cooling Tower Fundamentals and Application Principles", Marley Company (1967) and "Cooling Tower Performance Curves," Cooling Tower Institute (1967). Up-to-date articles on individual topics in the cooling water field are ubiquitous, and only the articles deemed to be most important are included herein.

A good pictorial introduction to the field outlining basic components and concepts is the special report "Cooling Towers" by Steve Elonka in the March, 1963 issue of Power Magazine. See also Figure X-1.

B. Definitions

Certain specialized definitions are required to read the literature in this field. They are:

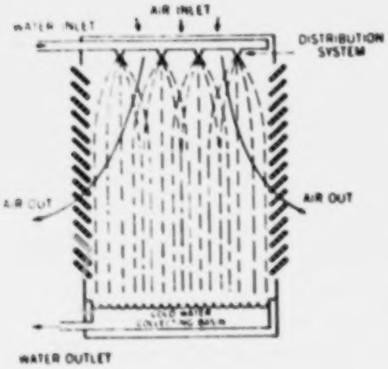
Cooling range or range: The number of degrees water is cooled from inlet to outlet of device.

Approach: The difference in temperature of the cold water leaving and the wet bulb temperature of the air entering. Without special treatment water cannot be cooled in a water cooled device to a temperature lower than the wet bulb ambient temperature. It has been suggested by Agnon and Young (1952) that it is possible to reduce the wet bulb temperature of the incoming air below ambients by passing the incoming air through an air cooler or heat exchanger before being admitted to the tower proper. The coolant used was part of the chilled water from the tower.

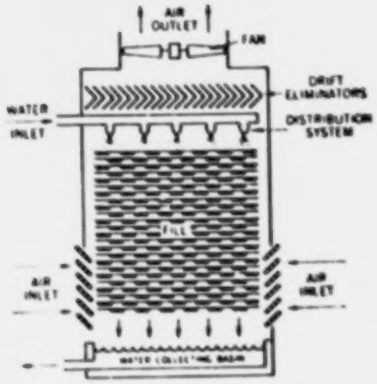
Heat Load: Amount of heat dissipated per unit time in the cooling device. It is equal to the weight of water circulated per unit time times the approach.

The heat load can be increased by:

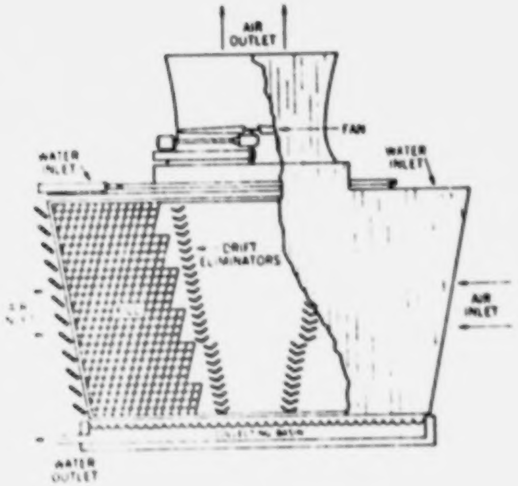
1. Increasing the velocity of the air in contact with the water surfaces.


WATER INLET
AIR INLET
DISTRIBUTION SYSTEM
AIR OUT
AIR OUT
COLD WATER COLLECTING BASIN
WATER OUTLET

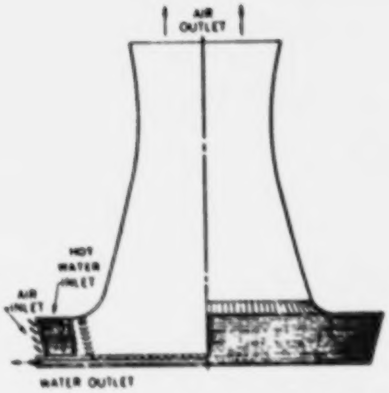
Atmospheric spray tower


AIR OUTLET
FAN
DRIFT ELIMINATORS
WATER INLET
DISTRIBUTION SYSTEM
FILL
AIR INLET
AIR INLET
WATER COLLECTING BASIN

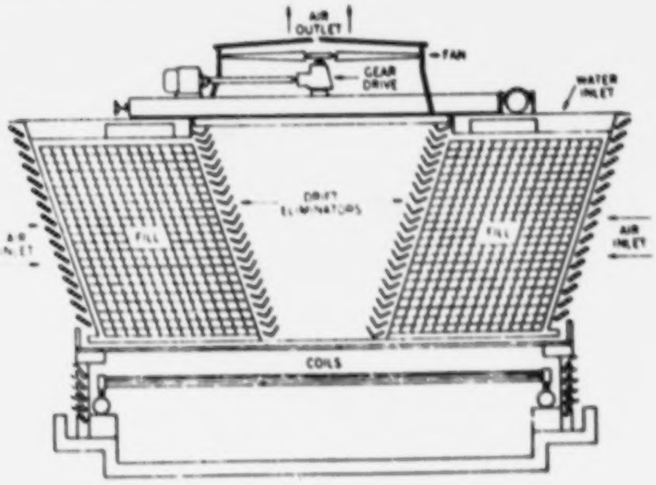
Counter-Flow tower


AIR OUTLET
FAN
WATER INLET
WATER INLET
DRIFT ELIMINATORS
FILL
AIR INLET
COLLECTING BASIN
WATER OUTLET

Cross-Flow tower


AIR OUTLET
HOT WATER INLET
AIR INLET
WATER OUTLET

Hyperbolic natural draft tower


AIR OUTLET
FAN
GEAR DRIVE
WATER INLET
DRIFT ELIMINATORS
FILL
FILL
AIR INLET
AIR INLET
COILS

Coil shed tower

FIGURE X - 1 SCHEMATIC OF COOLING TOWERS

2. Increasing the water surface exposed to the air.
3. Lowering the atmospheric pressure.
4. Raising the entering water temperature.
5. Reducing the vapor content of the inlet air.

Performance: The measure of the device's ability to cool water. Usually expressed in terms of cooling a quantity of water from a specified hot water temperature to a specified cold water temperature at a specific wet bulb temperature.

It should be noted and stressed that circulating cooling water device selection is intimately associated with condenser and turbine design and operation.

Though one can make approximate statements on the effect of decreased vacuum, increased pressure, initial temperature, increased reheat temperature and increased feed water temperature, the efficiency of the turbine and the resultant heat rate, (efficiency - BTU's required to produce 1 kilowatt hour of electricity) for any specific installation for the most economic solution it is necessary to take into account the interrelationships of the following factors (Devereaux, 1966).

1. average annual duration of temperature and humidity at the site,
2. condenser heat loads and vacuum correction curves for the turbines desired,
3. thermal performance of a number of cooling towers,
4. rough calculation of the pump and pipe network to determine costs and hydraulic characteristics,
5. performance of a number of condensers designed for the heat loads and cooling ranges under study,
6. costs of each component and thereby the amortization charges, fuel costs, plant lifetime load factor, and incremental capability credit.

As LeBailly (1951) noted, "There is no practical and simple formula to compare directly the combined performance of different combinations of condensors and cooling towers operating under the same heat load and wet bulb temperature."

C. Atmospheric Towers

This discussion will be limited to the types of cooling towers that are used with large modern central electric generating stations. It should be noted, however, that in 1967, electric utilities cooling tower requirements were only $20 million out of a total $70 million annual sales of cooling towers (Fluor-o-scope, Fall 1967). It should also be noted that in the time period 1962 - 1967, over 85% of the cooling towers installed in United States Power generating stations has been of the induced cross flow design (Hansen and Parker, 1967). Atmospheric towers are no longer used because they cannot provide the large cooling capacity required.

D. Mechanical Draft Wet Cooling Towers

1. Theory

All wet cooling towers are essentially described by the Merkel formulation (total heat method) (Merkel, 1925):

$$\frac{K_G\ dA}{Lc_s} = \frac{dti}{i_i - i_G} \qquad \text{X-1}$$

where:

K_G = mass coefficient of heat transfer

A = surface area

C_s = specific heat of the air/water vapor mixture

L = weight of water circulating per unit time

t_i = interface temperature between water and air

i_i = enthalpy at interface temperature (t_i)

i_G = enthalpy of moist air at temperature t_G

t_G = air temperature

The total heat transfer per unit area per unit time is a function of the difference between the air/water interface and the air temperature and the difference in concentration of water vapor in the saturated air at air/water interface temperature and the humidity of the main air stream. The first difference takes into account the sensible heat transfer and. the second, the evaporative heat transfer. The two heat transfer forces can be summed into the single equation shown where the difference in entering and leaving interface water temperature is a function of the differences in enthalpy between the interface air and the moist air. To maximize heat transfer, then the difference in enthalpy must be maximized.

In addition, the heat dissipated can be increased by:

1. Increasing the velocity of the air past the water surface as that increases both the sensible heat transfer and the evaporative cooling;
2. Increasing the surface area of water exposed to the flowing air again increases sensible heat transfer and evaporative heat transfer;
3. Lowering the atmospheric pressure increases the evaporation rate;

4. Raising the entering water temperature will increase the sensible heat loss and evaporation rate;

5. Reducing the vapor content (humidity) of the inlet air will increase the evaporation rate.

2. Advantages and Disadvantages of Mechanical Draft Wet Cooling Towers

Mechanical draft towers are divided into two categories, forced air flow or induced air flow. The advantages and disadvantages of both are listed below (McKelvey and Brooke, 1959).

a. Forced Draft Towers

Advantages

1. absolute control over air supply - correct quantities of air and suitable air velocities may be selected;
2. close control of cold water temperature;
3. small ground area required;
4. generally low pumping head;
5. location of the tower is not restricted;
6. more packing per unit volume of tower;
7. a closer approach and longer cooling range are possible;
8. capital cost is less than for a natural draft tower

Disadvantages

1. horsepower required to oeprate the fans;
2. subject to mechanical failure;
3. subject to recirculation of the hot humid exhaust air vapors into the air intakes;
4. maintenance costs are high;
5. operating costs are high;
6. performance will vary with wind intensity;
7. not suitable for all climatic conditions.

b. Induced Draft Towers

Induced draft towers are subdivided into crossflow and counterflow towers.

i. Counterflow Induced Draft Tower

Advantages

coldest water contacts the driest air and the warmest water contacts the most humid air. Maximum performance is thus obtained.

Disadvantages

1. Greater resistance to inlet flow of air increases the fan horsepower;
2. Greater resistance to upward flow of air through falling water requires a greater fan horsepower than in cross draft towers;
3. Uneven distribution of air velocities through the filling;
4. Moisture eliminator area restricts air flow;
5. High pumping head necessary;
6. Water load capacity is limited;
7. Hot water distribution system is inaccessible for ready maintenance;
8. High inlet velocities are liable to suck airborne trash and dirt into the plant.

ii. Cross flow draft tower

Advantages

1. Low pumping heat;
2. Low static pressure drop on the air side;
3. Convenient arrangement of the distribution system;
4. Possible to clean the distribution system while tower in operation;
5. The fill height is approximately equal to the tower height;
6. More air per fan horsepower;

7. More wood fill cooling surface per cubic foot of tower volume;

8. Higher water loadings are possible for a given height;

9. The water temperatures in the basin vary from the center to the edges according to a definite pattern, so that water may be drawn off at a selected temperature;

10. Larger diameter fans can be used so that fewer cells are required for a given capacity.

Disadvantages

1. An insufficient pressure head on the distribution pans to keep the orifices from becoming clogged;

2. Entire water feed exposed to the air which favors growth of algae;

3. A substantial crossflow correction factor needs to be applied to the driving force, particularly where long range and close approach performances are required. In such cases for some pumping heads a crossflow tower may need more ground area, and more fan horsepower than a counterflow cooling tower.

The major characteristics of induced draft towers - crossflow and counterflow - have been compared (Marley,1967).

a. Plan area - Counterflow units use less plan area than cross flow. Closer approaches can be obtained by simply increasing the height of the tower if space is a problem.

b. Low draft loss - for a specified applied horsepower a greater air flow is possible in crossflow towers because of lower static losses and therefore the crossflow tower is more efficient.

c. Thermal performance - crossflow towers can usually attain better thermal performance (i.e. heavier water loadings, longer ranges, and closer approaches) because the air flow distance is independent of fill height and static losses are not increased as length of air travel increases.

d. Low pumping head - static head is constant for cross flow towers but increases as depth of fill increases for counter flow towers. In addition, counterflow units which use spray nozzles require sufficient pressure to break up and distribute the water properly across the tower.

e. Recirculation - recirculation is less likely in cross flow towers than in counter flow towers. When it does occur in cross flow towers only the upper section of the tower is usually affected. In counter flow towers, the recirculation is likely to be more uniformly distributed, hence decreasing efficiency.

f. Multiple cold water temperature withdrawal - in cross flow towers, the temperature of the water in the towers decreases from the edge to the center of the tower. By dividing the tower, it is possible to extract cold water at various temperatures.

g. Winter operation - wide louvers inclined to the vertical enable warm water to be diverted to the sides and to keep the air flow spaces open.

For the above reasons, crossflow towers are most commonly used.

Though forced air flow towers would seem to have overwhelming advantages over induced flow towers such as fewer vibrational problems (fans located at intakes at lower levels), less corrosion since the fans contact the ambient (relatively dry) air, lower noise levels, and slightly more efficiency, (since some of the velocity pressure is extracted in useful work), their drawbacks are even greater. Recirculation of the moist, warmed air to the air intakes of the tower is greater than in induced air flow; uniform air distribution through the forced air draft tower is also more difficult to obtain in the large sizes, and fan size is limited in comparison to the size of fan utilized in induced air towers. Consequently, for the uses discussed here, induced draft towers are much favored over forced draft towers, and crossflow induced towers over counterflow induced draft towers.

Due to the competition from hyperbolic towers and the ever increasing demand for higher efficiencies many recent improvements have been made in mechanical draft cooling towers (Dickey, 1964). The use of single flow towers where space is a problem or where the wind flows predominantly in one direction has increased efficiencies more than 10%. The single flow arrangement can also be useful in preventing freezing by having the northern face solid. Fan and fan cylinder design have been advanced in recent years. Fan blade shape has come closer to the theoretical, and cylinders have incorporated energy recovery shapes. Various towers have been built to maintain their initial efficiency and to handle water temperatures up to 200°F (Anonymous, 1969).

E. Natural Draft Wet Cooling Towers

Natural draft towers have been used in Europe as far back as 1907. The first concrete hyperboloidal shell for a natural draft tower was installed in 1916 at the Emma Pit, Heerlen Coal Mine in the Netherlands (McKeivey and Brooke, 1959). Though these towers have been popular in Europe for many years, only recently have any been built in the United States.

Over one half of the generating capacity in the post World War II construction program for Great Britain utilized natural draft cooling towers (Chilton, 1952). The first natural draft tower was built in the United States in late 1962 at the Big Sandy Plant of the Kentucky Power Company. Possibly the reluctance to build natural draft towers in the United States was due to the fact that they appear, in general, to be best suited economically for areas with high humidities. Such areas in this country, eastern and northwestern U. S., also have had abundant water and loose temperature rise restrictions and consequently have used once-through river cooling. Now with greater demands on the available water and tighter water temperature rise restrictions, new attention has been given to the natural draft towers. Among the advantages of natural draft towers are long term maintenance-free operation (no moving parts and a concrete shell), smaller amount of ground space for multiple towers (no circulation of warm air from one tower to another), reduced piping costs (towers can be located adjacent to plant), no electricity required for operating fans, fewer electrical controls, and less mechanical equipment. Disadvantages include a decreased ability to design as precisely as for mechanical draft towers, and inability to control outlet temperatures as closely as in a mechanical draft towers.

McKelvey and Brooke (1959) indicate the following advantages and disadvantages for the hyperbolic natural draft towers.

1. Advantages
    a. They produce cooling effects similar to those provided by mechanical draft towers without the mechanical parts and the power required to run them;
    b. Maintenance costs are negligible;
    c. They can practically never break down;
    d. Compared with atmospheric towers they are independent of wind velocity;
    e. They can cope with tremendous water loads;
    f. They use comparatively small ground areas;
    g. The stream of air is in the opposite direction to that of the falling water with the coldest air meeting the colder water first which insures no loss in efficiency.
2. Disadvantages
    a. Resistance to air flow must be kept at a minimum, hence grid sections must be shallow unless some form of film flow is used;
    b. The great height necessary to produce the draft;

c. Inlet hot water temperature must be kept hotter than the air dry bulb temperature;

d. Exact control of outlet water temperature is difficult to achieve.

F. Natural Draft Wet Cooling Towers Theory

The basic theory of natural draft cooling towers was recently restated by members of England's Central Electricity Generating Board (Rish and Steel, 1959). They point out that the reason for the hyperbolic shape is aerodynamic and structural rather than thermodynamic, also substantially less material is required for the hyperboloid shape than for an equivalent straight cylindrical tower. (Jones, 1968) The shell is designed by membrane theory and results in extremely thin sections, as little as 5 inches of reinforced concrete, for towers over 300 feet in height. Details of the analysis including wind measurements, movement of the structure as it becomes saturated, icing, makeup and integration with the rest of the equipment in the power station are given.

Chilton (1952) had pointed out that the Merkel total heat equation was applicable to counter flow cooling towers in which the air flow is known. When the air flow is more variable and a function of climate and loading, such a direct solution is not possible. Wood and Betts (1950) have provided a trial and error solution to the problem but the method requires knowledge of constants which are difficult to evaluate. Chilton has derived an approximate solution which is valid if the air becomes saturated during flow through the tower packing. The duty coefficient of the natural draft tower (D), defines the overall capabilities of a tower under all operating conditions. It is essentially a constant over the normal range of operation and is a function of total heat of the air passing through the tower (Δh), the change of temperature of the water passing through the tower (ΔT), the water load in lb. per hour (W_L), and the temperature difference between the dry bulb and wet bulb air temperature (Δt).

$$D = \frac{W_L}{90.59 \frac{\Delta h}{\Delta T} \sqrt{\Delta t + 0.3124 \quad \Delta h}} \qquad (X-2)$$

The draft, then, is due to the difference between the density of the air leaving the tower and the density of the air entering the tower and to the aerodynamic 'lift' of the wind passing over the top of the tower.

Cranshaw (1963 - 1964), in a comprehensive series of tests, has more recently studied the variation of performance of natural draft towers and found:

1. That the air temperatures should be measured at both top and bottom of the fill;
2. Frictional resistance of the fill and the water to air loading are strongly effected by their change, especially at half loadings where the difference can be as great as 4 to 5°F;
3. Wind has a lesser effect at full loading than at half loading on tower performance and high winds cause a 2°F drop in the cooling range at half load;
4. Performance is negligibly effected by barometric changes;
5. Air stability conditions do reduce the cooling range an inversion by 1.2°F and a neutral lapse by 0.7°F;
6. Increase in loading cooling range, and humidity all tend to improve cooling tower performance.

It should be noted that all of these results were obtained under English climatic conditions.

Stern (1967) outlines some important items for consideration in choosing natural draft towers.

1. Temperate climate with above average humidity.
2. Lesser ground area for hyperbolic towers.

3. Height of effluent exhaust will mean less air pollution problems.

Technical factors to be considered are:

1. Tower spacing - at least one and one half times base diameter;
2. In cross flow towers, utilizing splash cooling, the fill is outside the shell and increases the diameter of the cold water basin. In the counter flow towers the fill is inside the tower and utilizes film cooling;
3. Packless, or spray filled towers, seem to hold some promise.

Jones, (1968), has noted that the market for natural draft cooling tower is almost equally divided between cross flow and counter flow towers. For a specific cooled water temperature higher ambient wet bulb conditions can be tolerated at higher humidities. For a given tower diameter as the approach narrows the water flow must decrease. The height of towers increased dramatically in the last 10 years, from approximately 300 feet to close to 450 feet. Evaporation losses average about 1.5% of the circulating water, and drift will not exceed 0.2% of the circulating water.

Cross flow towers utilizing wood fill are slightly cheaper to build than counter flow towers. However, the maintenance costs are higher since the wood will eventually have to be replaced, and the operating costs will also be higher, since 10 to 15% higher heads are required than in an equivalent counter flow design.

G. New Designs for Cooling Towers

Experimental designs for more efficient cooling towers are under development. Space requirements for both hyperbolic and induced draft towers are so great that combining the best features of both would reduce the space required, improve the efficiency and reduce the variability of performance. Therefore, mechanical draft has been added to hyperbolic towers to achieve this higher efficiency. The Central Electric Research Laboratories, England, has completed such a design for an assisted-draft tower raising the capacity of a natural draft tower from 250 to 660 megawatts (Stubbs, 1968). In addition, model designs of ellipsoidal form have been tested to separate the airflow and to help create a high draft velocity. In addition, such a slope will help prevent downdrafts into the tower. Such towers would reduce aerodynamic interaction between closely spaced shells (which was partially responsible for the Ferrybridge collapse) and, in addition, would be less conspicuous and occupy less land. (Anonymous, 1967)

H. Dry Cooling Towers

The discussion above pertains primarily to wet cooling towers (i.e., those towers where the major mode of heat dissipation is evaporation.) For certain cooling conditions such as very high water temperatures, insufficient water, and problems of blowdown disposal, systems that depend primarily upon convection and use air as the transport medium may be preferable. (Dry cooling towers may be either of the natural draft or mechanical draft types.) McKelvey and Brooke list the following advantages and disadvantages of dry cooling towers:

1. Advantages
   a. It can be used where fluids to be cooled are at a high temperature;
   b. It eliminates water problems such as availability, chemical treatment, corrosion, spray nuisance, freezing hazard and fouling;
   c. There is no upper limit to which air can be heated.
2. Disadvantages
   a. Normally a dry cooler is less economical than a cooling tower of the ordinary evaporative type;
   b. The specific heat of air is only one-fourth that of water;

c. Maintenance costs, e.g., the prevention of corrosion are high.

I. Dry Cooling Tower Theory

Though air cooling has been used for many years for industrial cooling in the petroleum industry and in automobiles, it was only with the recent work of Heller and Fargo (1956, 1962) that the theory advanced sufficiently to permit larger scale application to Central Electricity Generating Station. As early as 1939, Gesellschaft fur Luftkondensation (GEA) had installed an air cooled condenser on a high vacuum stationary steam turbine. The design was the familiar finned tubes with air cooling (GEA, 1969).

In the unique design of Heller, the exhaust steam from the turbine is sent to a direct contact spray-type jet condenser using cooling water of feed water quality. As shown in Figure X-2, the condensate is then circulated to the air cooled tower. The entire system is kept under pressure to avoid air leakage.

In addition to a 16 MW plant in Hungary, two 6 MW plants in the Soviet Union, two 7.5 MW plants in Pakistan and a 120 MW plant in Rugeley, England have been constructed. The Rugeley plant has been in successful operation for over 7 years (Fiehn, 1969). The turbine operated at a steam pressure of 1500 psig and steam temperature of 1000°F and reheat to 1000°F and the tower dissipates 587 x 10^6 BTU/hr with a water savings of 1.8 x 10^6 gallons per day (Christopher, 1965). The application of the spray condenser to steam turbine was the idea of Heller but the success of the system depended upon having a highly efficient and cheap heat exchange. This was designed by Fargo. To prevent excessive corrosion 99.5% pure aluminum was used and the joints were mechanical rather than welded or brazed. The tower was the largest in the world at that time reaching 350 feet and having a base diameter

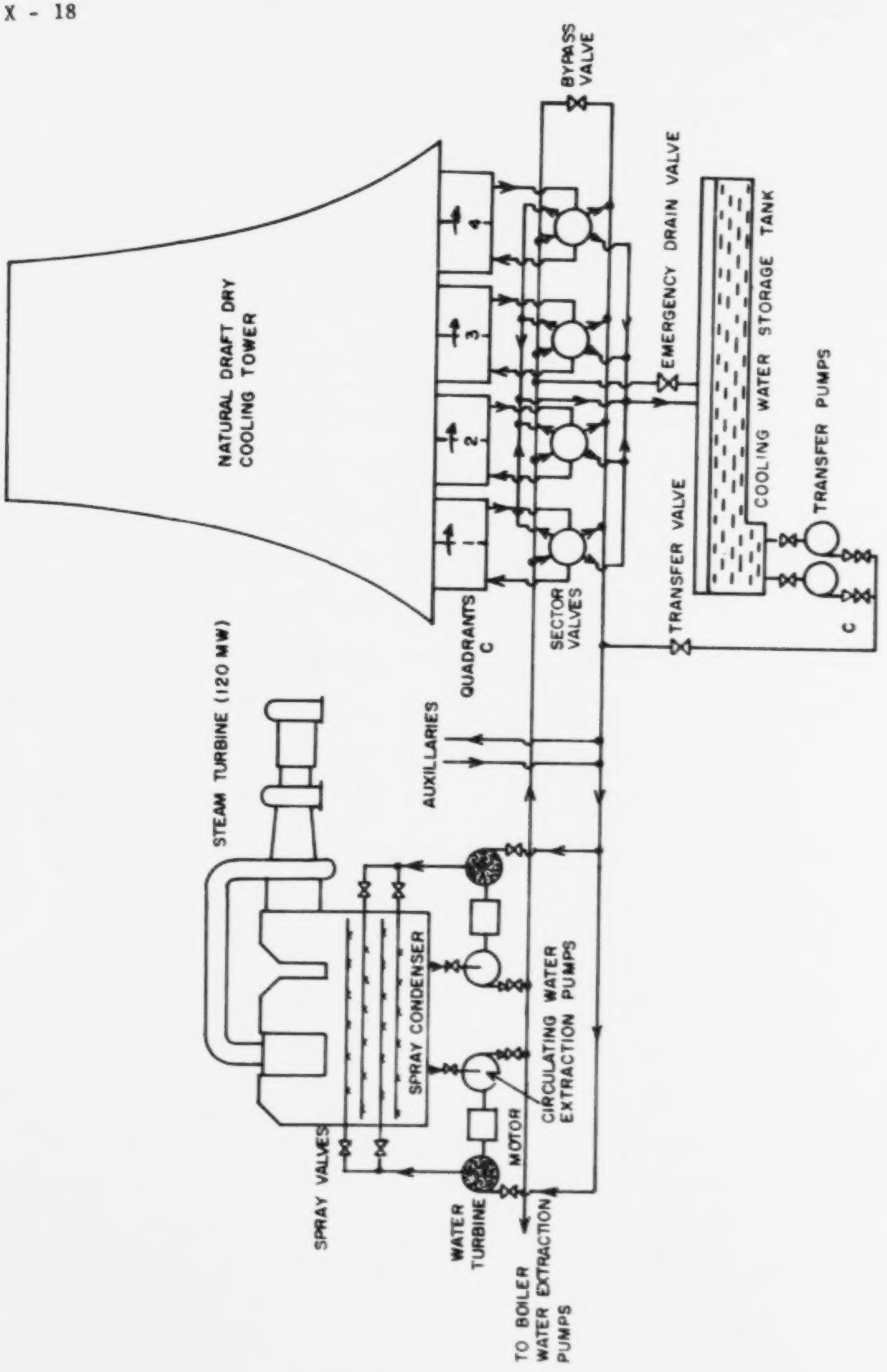

STEAM TURBINE (120 MW)
NATURAL DRAFT DRY COOLING TOWER
1
2
3
4
QUADRANTS C
SECTOR VALVES
BYPASS VALVE
EMERGENCY DRAIN VALVE
COOLING WATER STORAGE TANK
TRANSFER PUMPS
TRANSFER VALVE
C
AUXILIARIES
SPRAY CONDENSER
CIRCULATING WATER EXTRACTION PUMPS
MOTOR
SPRAY VALVES
WATER TURBINE
TO BOILER WATER EXTRACTION PUMPS

FIGURE X - 2 HELLER TYPE DRY COOLING TOWER SYSTEM

of 325 feet. The tower and condenser went into full service in July 1962. Makeup water in the first three years (for boiler flowdown and other losses) averaged about 2 percent. The system has been judged to be a complete success. Designs have been proposed for stations up to 4000 MW capacity and the English Electric Company expects the dry towers to become a common feature of power stations in the future. (Anonymous, 1965)

Recently a 150 MW unit at Ibbenburen, West Germany has been placed in operation and a 200 MW turbine and two 100 MW turbines at Gyongyos, Hungary are being installed (Jaszay and Tomcsanyi, 1968).

J. Research Required

1. Though cooling tower design has evolved over a long period of time and has reached a high state of development, it would still be useful to study from a basic principle point of view the heat transfer mechanism in a cooling tower. It may be that the utilization of tortuous surfaces would result in longer flow-through times and consequently increase evaporation for a given air flow.
2. The interference of multiple towers on each other versus the costs of longer towers should also be studied.
3. The physical and economic limit of towers should be studied. It may be that the efficiencies of scale of prime movers are completely negated by increased tower and pollution costs.
4. Dry cooling towers have only been built in small sizes. The physical and economic problems of extrapolation to larger sizes should be investigated.
5. The shape of towers is not aerodynamically efficient with respect to air flow across the towers. Changes in shape to reduce the recirculation and improve air flow out of the towers should be studied.

6. The design and efficiency of fan assisted natural draft towers should be investigated to determine the possible savings in tower size and ground space. The increase in the rise of the tower plume should also be studied.

BIBLIOGRAPHY

Agnon, S., and Chia-Yung Young, 1952, "Cooling of Water Below Web-Bulb Temperature of Ambient Air by Cooling Tower". *Heating, Piping, and Air Conditioning*, *24*, 139.

Anonymous, 1965, "Experience at Rugeley Establishes Design and Use of Dry Cooling Towers". *Power Engineering*, *69*, 62.

Anonymous, 1967, "Ellipsoidal Cooling Tower Promises High Efficiency". *Power*, 95.

Anonymous, 1969, "Ceramic Cooling Towers", Ceramic Cooling Tower Company, Fort Worth, Texas.

Babcock and Wilcox, 1963, "Steam - Its Generation and Use". Babcock and Wilcox, New York, N. Y.

Berman, L. D., 1961, "Evaporative Cooling of Circulating Water". Pergamon, New York, N. Y.

Chilton, H., 1952, "Performance of Natural-Draught Water Cooling Towers." Proc. Institution Electrical Engineers, *99*.

Christopher, P. J., 1965, "The Dry Cooling Tower System at the Rugeley Power Station of the Central Electricity Generating Board." *English Electric Journal*, *20*, 22-33.

Cooling Tower Institute, 1967, "Cooling Tower Performance Curves." Cooling Tower Institute, Houston, Texas.

Cootner, P. H., and Lof, G. O. G., 1965, "Water Demand for Steam Generation". Johns Hopkins, Baltimore, Md.

Crawshaw, C. J., 1963-1964, "Investigation into Variations of Performance of a Natural-Draught Cooling Tower". *Proc. Inst. Mechanical Engineers*.

Devereaux, M. B., 1966, "Selecting Integrated Cooling Tower-Condenser-Turbine Combination". *Am. Power Conference Proc.*, *28*, 457-68.

Dickey, Joe Ben, Jr., 1964, "Large Mechanical Draft Towers Show Many Recent Improvements". *Power Engineering*, 30.

Elonka, S., 1963, "Cooling Towers". *Power*, *107*, S1 - S16.

Fiehn, A. J., 1969, "Cooling Tower Applications in Power Cycle Design". Journal Power Division American Society of Civil Engineers, 95, 55.

Fluor-o-scope, 1967, Fluor Corporation, Los Angeles, Calif.

GEA, 1969, "Air Cooled Steam Condenser". GEA, Bochum, Germany.

Hansen, E. P., and Parker, J. J., 1967, "Status of Big Cooling Towers". Power Engineering, 38.

Heller, L. I., and Fargo, L., 1956, "Operational Experiences With the Condensation System of a Power Plant With Air-Cooled Water Circuit and Potential Improvements". Fifth World Power Conference.

Heller, L. I., and Fargo, L., 1962, "Recent Operational Experiences Concerning the 'Heller' System of Air Condensation for Power Plants. Latest Results of Developments." Sixth World Power Conference.

Jaszay, T., and Tomcsanyi, G., 1968, "A Survey of Air-Cooled Condensing Plants 'System Heller'." Transelektro News, 9, 32-33.

Jones, W. J., 1968, "Natural Draft Cooling Towers," presented at Cooling Tower Institute Annual Meeting.

LeBailly, A. R., 1951, "Some Economic Factors in the Selection of Cooling Towers." Transactions American Society Mechanical Engineers, 73, 1021.

Marley Company, 1967, "Cooling Tower Fundamentals and Application Principles." Marley Company, Kansas City, Mo.

McKelvey, K. K. and Brooke, M. E., 1959, "The Industrial Cooling Tower." Elsevier, Amsterdam.

Merkel, F., 1926, Zeitschrift des Vereines Deutscher Ingenieure, 70, 123.

Rish, R. F., and Steel, T. F., 1959, "Design and Selection of Hyperbolic Cooling Towers," ASCE - Proc. (J. Power Div.),85, 89-117.

Skrotzki, Bernhardt, G. A., and Vopat, William A., 1960, Power Station Engineering and Economy, McGraw Hill, New York, N. Y.

Stern, W. M., 1967, "Hyperbolic Cooling Towers," Power, 59-62.

Stubbs, C. T., 1968, "Cooling Tower Designs Improved." Electrical World, 108.

Wood, B. R., and Betts, P., 1950, "A Temperature - Total Heat Diagram for Cooling Tower Calculations." The Engineer, 189, 455-457.

CHAPTER XI -1

COOLING TOWER PROBLEMS

Though in many respects cooling towers seem to offer overwhelming advantages and to be an absolute necessity in some instances, they are not without their own problems. The wet towers, both mechanical and natural draft, have perhaps more problems than the dry towers but, in general, they are also less costly. Some of the problems are described in the following section.

A. CLIMATIC EFFECTS OF COOLING TOWERS

The use of the atmosphere as a sewer to carry off our wastes is well established, and is favorably looked upon even by professional meteorologists provided that it is done under the proper conditions and with no ill effects (Smith, 1963). For dry heat injection this feeling is even more pronounced, and professional meteorologists indicate that this discharge into the environment is acceptable and preferred to discharges to the hydrosphere or lithosphere (Personal communication, Thom, July 1969).

Among the first problems to be answered is the question of major climatic changes due to waste heat rejection to the atmosphere. It has been shown that the amount of heat rejected from our major cities is a not negligible fraction (3%) (Brooks, 1967) of the solar heat reaching the earth's surface for that region. At present over the entire earth's surface the yearly production of man-made energy is about 1/2500 of the radiation balance of the earth's surface. It could equal the surface radiation balance if compounded annually at 10% for 100 years (Fletcher, 1969). Its present growth rate is 4% per year. Therefore, even if we alleviate local thermal pollution problems now, the global problem will be upon us in a few decades. In the meantime the following general conclusions have been reached (Fletcher, 1969).

"(1) It does appear to be within man's engineering capacity to influence the loss and gain of heat in the atmosphere on a scale that can influence patterns of thermal forcing of atmospheric circulation.

(2) Purposeful use of this capability is not yet feasible because present understanding of atmospheric and oceanic dynamics and heat exchange is far too imperfect to predict the outcome of such efforts.

(3) Although it would be theoretically more efficient to act directly on the moving atmosphere, engineering techniques for doing so are not presently available.

(4) The inadvertent influences of man's activity may eventually lead to catastrophic influences on global climate unless ways can be developed to compensate for undesired effects. Whether the time remaining for bringing this problem under control is a few decades or a century is still an open question.

(5) The diversity of thermal processes that can be influenced in the atmosphere, and between the atmosphere and ocean, offers promise that, if global climate is adequately understood, it can be influenced for the purpose of either maximizing climatic resources or avoiding unwanted changes."

The second problem is the effect of cooling towers on regional climatology. The professional opinion is that cooling towers will not have a measurable effect on a region's climatology. This opinion is based upon the effect of Lake Meade and similar large scale man-made systems upon the local climatology. (Personal communication, Holzman, July 1969).

This was recognized as long ago as 1937 when Holzman stated "that the moisture for precipitation in the United States was derived mainly from the oceans and transported by maritime air masses". (Holzman, 1941).

This is not to imply that cities do not have a measurable effect on their climate. Landsberg (1961) showed that cities did have a profound influence as illustrated in Table XI-1. Landsberg (1961) notes "that the influences of the city on precipitation are not easily unraveled. We can say with reasonable confidence, however, that most of them tend to increase precipitation."

The main causes for increased precipitation are: additional water vapor from combustion processes and factories; added nuclei of condensation and freezing; thermal updrafts from local heating; and updrafts from increased friction turbulence. Chagnon (1961) notes the urban effect on precipitation is most pronounced in the colder half year of humid continental climates. Though Chagnon (1961) notes increases in precipitation over the Champaign-Urbana region, he concludes "whether a given city produces, or can produce, a 5, 10, or 15 percent increase in rainfall and number of rainy days in portions of its urban area is a question that neither meteorology nor climatology can at present answer accurately".

More recently Czapski (1968) has suggested that the climatic effects "observed" near cities may be due more to the effect of the added heat than the condensation and freezing nuclei to which they are usually attributed. Czapski foresees severe consequences of large latent heat and thermal emissions:

(1) rainfall will be increased downwind for a considerable distance,

(2) cumulus clouds will prevail most of the time downwind from a large power plant, and

TABLE XI-1

CLIMATIC CHANGES PRODUCED BY CITIES

Element	Comparison with Rural Environs
Contaminants:	
dust particles	10 times more
sulfur dioxide	5 times more
carbon dioxide	10 times more
carbon monoxide	25 times more
Radiation:	
total on horizontal surface	15 to 20% less
ultraviolet, winter	30% less
ultraviolet, summer	5% less
Cloudiness:	
clouds	5 to 10% more
fog, winter	100% more
fog, summer	30% more
Precipitation:	
amounts	5 to 10% more
days with 0.2 in.	10% more
Temperature:	
annual mean	1 to 1.5°F more
winter minima	2 to 3°F more
Relative Humidity:	
annual mean	6% less
winter	2% less
summer	8% less
Wind Speed:	
annual mean	20 to 30% less
extreme gusts	10 to 20% less
calms	5 to 20% less

(3) severe thunderstorms and even tornadoes can be caused in very unstable weather by dry and clear heat.

Thom (Personal communication September 1969) has pointed out that most of the estimates about climatic effects upon cities are speculative and the interpretation of many of the observations about climate are subject to question.

Hall, Russell, and Hamilton (1958) have noted that even for major ecological changes such as forests, the most noticeable effect on the microclimate occurs within the forest itself. For shetler belts, the microclimate of the adjacent open areas is most affected.

There is no question that man can modify his local rainfall temporarily as seen in the rain after the fire bombings in Tokyo and Hamburg. It does not seem that the energy and moisture released from cooling towers has yet reached that level, but it is a fruitful area for research.

B. FOG AND PLUMES FROM WET COOLING TOWERS

Localized ground fog does occur around many cooling towers when the cooling air water vapor saturation exceeds the capacity of the ambient air for water vapor (Buss, 1968). It is suggested that the physical location of the cooling tower be adjusted so that the fog does not obscure roadways or other industrial buildings. One method used to reduce ground fog was to increase the height of the discharge stack to enable the fog to diffuse before reaching the ground. In addition, individual discharge stacks were used for each fan cell to reduce the obstruction to air flow and, consequently, reduce downdrafts (Baker, 1960). Another ingenious method was to heat the cooling tower exhaust air so as to increase its velocity, heat content and to promote greater turbulence so that the mixtures were below saturation (Hall, 1962).

The prediction of the size and path of the fog from cooling towers is possible by analogy with smoke plumes. The angle of the spread of the plume usually varies from 18 to 24 degrees and the length of the visible plume was

$$Xp = 5.7 \left(\frac{Vg}{102.\pi.Vw} \right)^{\frac{1}{2}} \cdot \left(\frac{tge - tgi}{tp - tgi} - 1 \right)^{\frac{1}{2}} \qquad \text{XI-1}$$

where tg = air or plume temperature (°C)

tp = temperature at end of visible plume (°C)

Vw = wind speed (ft/s)

Vg = total rate from tower (m^3/h)
(N.B. All gas volumes refer to 20°C and 1 atm. pressure)

Xp = visible plume length (ft)

Suffixes

i = inlet

e = exit

Longer and lower plumes occur when air temperature is low, humidity high, and wind speed moderate to high (Baker, 1967).

C. NOISE

Large, high speed, rotating machinery and enormous quantities of air moving through restricted spaces cause noise. Consequently, around mechanically induced draft cooling towers, there is going to be high sound levels. A three-step procedure is followed to evaluate noise problems (Miller and Long, 1962). First, using established values, determine the sound levels that will be acceptable to the neighboring installations. (In most instances, the building served will be insolated from the outside noise.) Background noises may mask the tower noise.

Second, estimate the noise level produced by the cooling tower installation and received at the neighboring site. Make sure that all electrical and water connections are isolated from the tower and the only noise is one from the tower operation itself. Third, if the sound level at the neighboring site is excessive, reduce it by any or a combination of the following methods:

A. Increase the wall density or thickness, close windows, close air vents, seal cracks, and barrier walls at the site.

B. Change orientation of the tower so that sound is projected in another direction; reflecting walls can be used.

C. Move the tower further away from the critical site.

D. Run fan motors at lower speed at night when load is lowest, but when ambient noise levels may also be lowest.

E. A more expensive but more effective method is to use a lined plenum chamber. A very complete set of curves and tables on acceptable sound levels, noise reduction provided by various walls, background noise, and distance correction values is given in the paper.

In a similar paper (Seelback and Oran, 1963), values of noise levels for fans of different horsepower are given. It is also pointed out that fan noise carries further and is more noticeable than water noise. Outlet noise is also greater than inlet noise, and satisfactory noise level reduction can sometimes be obtained by baffling the outlet only.

For more complete details on noise and its control, reference should be made to Noise Reduction by L. L. Beranek (1960), and to Handbook of Noise Control edited by C. M. Harris (1957).

D. CHEMICAL WASTES FROM COOLING TOWERS

To promote long serviceable life for cooling towers, algicides and fungicides must be used to prevent damage to the wooden components of cooling towers and corrosion inhibitors to prevent oxidation of the metal parts. These chemicals are a potential pollution hazard if discharged directly to the stream. The major references to these problems are: (1) Primer on Cooling Water Treatment by the National Association of Corrosion Engineers, 1966, Houston, Texas; (2) papers presented at the Cooling Tower Materials and Water Treatment Symposium at the 1965 meeting of the American Chemical Society, Illinois State Water Survey Circular 91, 1966; and (3) Berg, et al, 1964, Water Use and Related Costs with Cooling Towers. This paper was adopted from the Illinois State Water Survey Circular No. 86.

Scale and foulants adhere to heat transfer surfaces or settle out in low flow areas and reduce the efficiency of the cooling towers. Common types of scales are: calcium carbonate (most common), calcium sulfate, silica, magnesium compounds, iron and manganese compounds, and phosphate compounds. Scale prevention is enhanced by (1) softening the water (but this also increases its corrosiveness), (2) pH adjustment, which is not too satisfactory since conditions vary widely throughout the cooling tower, (3) chemical treatment of the water by the addition of polyphosphates which slow the rate of precipitation of the scale forming materials; polyphosphates with organics which primarily make the scale crystals non-adherent; and organics alone (occasionally for water extremely high in scaling tendencies).

The rate of corrosion can be reduced by the use of anodic and cathodic inhibitors. Typical inorganic, anodic inhibitors are sodium and potassium chromates, phosphates, silicates, nitrites, ferrocyanides, and molybdates. The chromates are most frequently used at high concentrations more than 200 ppm $Na_2\ CrO_4$ due to their relatively low cost and superior corrosion inhibition frequency.

Cathodic inhibitors may be salts of zinc, nickel, manganese and trivalent chromium. They do not appear to be as successful as anodic inhibitors.

Organic inhibitors are sometimes used but their chief use appears to be in conjunction with polyphosphate and chromates to improve their corrosion inhibition.

There are also a wide variety of proprietary compounds which are used to inhibit corrosion. They are mostly based on chromates and polyphosphates with some additives.

Biological fouling not only plugs screens and restricts flow in lines, it can through the photosynthetic process release oxygen to accelerate the corrosion process. The most commonly used agent to control biological growth is chlorine in shock loadings. However, the free chlorine residual in the hot return line to the tower should be less than 1 ppm to reduce chlorine attacks on the tower lumber. For cooling tower sumps where chlorine is not available, a wide variety of toxicants is available.

Cooling tower lumber to retain its strength should not be exposed to any strong oxidizing agent and can be protected from biological attack by using wood pressure treated with chromates and zinc. High temperatures across the wooden surfaces should be avoided to reduce changes in structure and loss of wood material (Primer on Cooling Water Treatment, National Association of Corrosion Engineers, 1966). A vast literature details treatment on these problems by proper material control, operation, and chemical treatment. Among the more useful are those by Dalton (1965) with a table of chemicals used for cooling water treatment including purpose, usual dosage, relative effectiveness, waste problems, and relative cost. Dinkel, et al, (1967) details the advantages of anti-foulants in extending operating periods. High molecular weight polymers prevent deposition by flocculation, and organics such as lignins and tannis disperse the potential fouling materials. Berg, et al, (1964) showed that chemical costs could be reduced if the mineral concentration in the cycled water could be increased 5 to 10 times rather than the common practice of 1 to 2 times. Recommendations for increasing the mineral concentration had previously been made by Denman, (1961). Berg, et al, (1964) gives estimates of all the various costs associated with cooling towers and for comparison purposes with once through cooling. It is this data which is used in Cootner's and Lof's Water Demand for Steam Electric Generation (1965). Details of the proper maintenance of cooling towers is given by Willa (1966). The right materials for use in cooling towers with information on their service under various exposure conditions is presented by Nelson (1966). For normal conditions, cast iron, modular iron, and galvanized steel for major mechanical and support parts, cast aluminum for blades, wrought aluminum for splash bars, copper alloys for nails, and redwood or pressure treated douglas fir for fill splash bars and framing, douglas fir plywood for fan decks, and hot water basins, glass fiber reinforced polyester for fan blades and cylinders, and polypropylene and high density polyethylene for orifices and spray nozzles are used.

Water effects of cooling towers are due primarily to the chemicals used for corrosion and fouling control. If the blowdown material cannot be rejected directly to the stream, ion exchange resins may be used to remove the chromates on streams and thereby, may even eliminate blowdown altogether. (Anonymous, 1964). A report by Hoppe, (1966), indicates that it may be possible to use a zinc and biodegradable organic without phosphate and chromate and that the blowdown can be discharged to the stream.

E. WATER QUALITY EFFECTS OF COOLING TOWERS

In passing through wet cooling towers, the temperature is reduced, the water is oxygenated, the BOD reduced, and the chlorine demand lowered (Dalton, 1965). Perhaps the most comprehensive paper on water quality changes in cooling towers has been based upon studies at English power stations ranging from 120mw to 600mw by Davies (1966). He points out that for a large, modern power station, blowdown can be as much as one million gallons per hour and this can be a sizable fraction of a stream. Since mostly pure water is evaporated, it would be expected that the concentrations of inorganics such as chloride, sodium, sulphate, totally dissolved solids, and conductivity increases directly as a function of a number of recirculations. This was found to be true in most cases for chlorides, in half the cases for sodium, and only in one-third of the cases for sulphate and conductivity. The hydronium ions (pH) at 3 of the 5 stations tested were concentrated slightly more than the inorganic constituents which appeared to be due to the loss of carbon dioxide to the air while passing through the tower. Other possible reactions which would lower the concentration of the hydronium ion below the recirculation concentration are oxidation of ammonia to nitric acid, hydrolysis of molecular chlorine to hydrochloric acid, and oxidation of sulphur dioxide. At three of the stations, hardness follows chloride concentrations, but in one station there appears to be precipitation of calcium carbonate.

The main chemical changes to water passing through cooling towers then, are the loss of carbon dioxide, consumption of some of the oxidizable matter, and nitrification of ammonia. These processes are accelerated by the heated waters over their natural rate of occurrence in streams.

F. DISCHARGE OF CONDENSER COOLING WATERS TO THE GROUND

Though few large central station power plants reject their condenser cooling waters to the ground, because of the magnitude of the flows, smaller size units do. The Dutch have taken a preliminary look (Dam, 1969) at the problem and concluded that fresh water, for their country is too valuable and would not be used. Saline and brackish water can be used, but will eventually raise ground water to temperatures whereby they cannot be used for cooling purposes. The Dutch also conclude, for their country, that the costs of recharging, maintenance, etc. are so great that, if possible, other methods of cooling should be used (Bardet, 1968).

The practice of using ground water for cooling is quite old in this country. By 1937, over 22 million gallons per day were being recharged to the ground formations in Kings and Queens Counties in New York (Leggette and Brashears, 1938) at an average temperature rise of 10°F to 15°F. In 1937, a rise of 9°F in the ground water supply due to recharge operations was noted (Leggette and Brashears, 1938). By 1940, recharge had reached 30 million gallons per day and ground water temperatures had risen as much as 20°F at some of the pumping wells (Brashears, 1941). By 1914, 60,000,000 gallons per day were being recharged and were causing gradual temperature rises in the ground water. These rises, however, were confined to areas near the recharge wells. In Nassau County, Long Island, New York, though high water temperatures have been found near some recharge wells, no widespread thermal pollution has been detected (DeLuca, et al., 1965).

It is interesting to note that a recent European paper on the influence of central electric generating stations on the ground water regime near rivers does not even mention thermal pollution as a problem (Stundl, 1967).

A beneficial use of the condenser cooling water discharged to the ground has been noted by Grauby (1966) who suggests a modification of production periods by creating a microclimate of several thousand hectares.

G. TOWER FAILURES

The most spectacular problem with cooling towers was the failure of three natural draft cooling towers at the Ferrybridge C Power Station in England. The prime mode of failure was a vertical tensile failure within the lower part of the structure (Hannah, 1967). The design of the structures was deficient in three areas:

(1) One minute maximum mean wind speeds were used whereas the structure was vulnerable to winds of shorter duration.

(2) No safety margin was left for uncertainties in steady or dynamic wind loadings.

(3) It was not appreciated how much the design could be changed by minor changes in the pressure coefficient distribution. The safety

factors were applied to the strength of materials rather than to the load.

No defect or deficiency in the material or workmanship on towers was found which could be considered to have contributed significantly to the collapse. The committee also found that insufficient attention had been paid to the effect of adjacent towers or the building itself in changing the wind loads (Anon., 1966).

H. Research Required

(1) Practically no information is available on the climatic effect of the discharge of large quantities of heat and water vapor into the atmosphere. The effects of dry cooling towers may be even more adverse than wet cooling towers. These changes should be compared to the changes produced by the heat, water vapor and particulate matter emitted by an urban complex.

(2) The size and path of fog from cooling towers has not been sufficiently well established. When the size and location are determined as a function of wind speed, air temperature and humidity and approach, then a non-interfering location can be specified.

(3) Means of preventing fog from becoming a nuisance need to be more thoroughly investigated. The degree of heating, induced turbulence, etc., that might be required needs to be detailed.

(4) More satisfactory means of handling the blowdown from cooling towers need to be found. The maximum number of recirculations compatible with the heat transfer properties, life of components and treatment need to be determined. If the blowdown contains many impurities, it may be

denser than the fluid into which it is discharged and would then become a negatively buoyant flow.

(5) Little information is available concerning negatively buoyant flows in flowing streams and under stratified flow conditions. The effect of the angle of discharge, the initial momentum, the flow of the ambient fluid, etc., need to be investigated to determine what conditions will induce complete mixing.

(6) There appear to be a number of improvements in the water quality of the cooling water passing through cooling towers. Some information on changes occurring in towers in England is available, but a more detailed study of conditions in the United States needs to be made. It may be possible, by suitable alterations of operating techniques to substantially improve the quality of the discharged water.

(7) The effects of multiple towers upon the wind stresses induced need to be elucidated. The Ferrybridge inquiry needs to be broadened to take into account the change in wind loadings due to their towers and the power station itself.

(8) The possible mixture of water vapor from cooling towers and sulfur dioxide from stacks needs to be considered. If the plumes mix, then an acidic condition can result with deleterious results. The effects of tower and stack spacing, height of plume rise, structure of the atmosphere, wind speed, etc., all play some role in this phenomenon.

BIBLIOGRAPHY

Anonymous, 1964, "Systems Recover Chromate from Cooling Water Discharge". *Chemical and Engineering Use*, 43.

Anonymous, 1966, "What Lessons from Ferrybridge". *Engineering, 201*, 401.

Baker, D. R., 1960, "Unique Cooling Tower Overcomes Ground Fog". *Oil and Gas Journal*, *58*, 78.

Baker, K. G., 1967, "Water Cooling Tower Plumes". *Chemical and Process Engineering*, *48*, 56-59.

Bardet, J., 1968, "Technical Aspects of Groundwater Recharging". *De Ingenieur*, A758.

Beranek, L. L., Ed., 1960, "Noise Reduction". McGraw-Hill, New York, N. Y.

Berg, B., Lane, R. W., and Larson, T. E., 1964, "Water Use and Related Costs with Cooling Towers". *Journal of American Water Works Association*, *56*, 311.

Brashears, M. L., Jr., 1941, "Groundwater Temperature on Long Island, New York, as Effected by Recharge of Warm Water". *Economic Geology*, 811.

Brooks, N. H., 1967, "Man, Water, and Waste", 110. California Institute of Technology, Pasadena, California.

Buss, J. R., 1968, "How to Control Fog from Cooling Towers". *Power*, *112*, 72.

Chagnon, S. A., Jr., 1961, "A Climatological Evaluation of Precipitation Patterns over an Urban Area", 45. Public Health Service, Cincinnati, Ohio.

Cootner, P. H., and Löf, G. O. G., 1965, "Water Demand for Steam Electric Generation". Johns Hopkins Press, Baltimore, Maryland.

Czapski, U. H., 1968, "Possible Effects of Thermal Discharges to the Atmosphere", 19. Proceedings Fifth Annual Environmental Health Research Symposium - Thermal Discharges, New York State Department of Health.

Dalton, T. F., 1965, "Cooling Towers: Problems and Some Treatment Practices". *Water Works and Wastes Engineering*, *2*, 53.

Davies, I., 1966, "Chemical Changes in Cooling Water Towers". Air and Water Pollution, 10, 853.

Deluca, F. A., Hoffman, J. F., and Lubke, E. R., 1965, "Chloride Concentration and Temperature of the Waters of Nassau County, Long Island, New York, U. S. Geological Survey, 5.

Denman, W. L., 1961, "Maximum Reuse of Cooling Water". Industrial and Engineering Chemistry, 33, 817.

Dinkel, C. C., Beecher, J. S., Corwin, S. H., 1967, "Anti-Foulants in Cooling Water Treatments". Industrial Water Engineering, 17.

Fletcher, J. O., 1969, "Managing Climatic Resources". Rand Corporation, Santa Monica, California, 3.

Granby, A., 1966, "The Heating of Soils Using the Cooling Cycle of a Power Reactor". Energie Nucleaire, 8, 193-4.

Hall, H., Russell, V. S., and Hamilton, C. D., 1958, "Trees and Microclimate". Climatology and Microclimatology, UNESCO, Paris, 259.

Hall, W. A., 1962, "Elimination of Cooling Tower Fog from a Highway". Journal Air Pollution Control Association, 12, 379.

Hannah, I. W., 1967, "I Resume of the Report on the Failures". Natural Draught Cooling Towers - Ferrybridge and After, Proceedings of the Conference held at the Institution of Civil Engineers, 5.

Harris, C. M., Ed., 1957, "Handbook of Noise Control". McGraw-Hill, New York, N. Y.

Holzman, B., 1941, "The Hydrologic Cycle in Climate and Man", U. S. Government Printing Office, Washington, D. C.

Holzman, B., 1969, Personal Communication.

Hoppe, T. C., 1966, "Coping with Cooling Tower Blowdown". Industrial Water Engineering, 27.

Illinois State Water Survey Circular 91, 1966, "Selected Papers on Cooling Water Treatment", Urbana, Illinois.

Landsberg, H. E., 1961, "City Air - Better or Worse". Public Health Service, Cincinnati, Ohio, 3.

Leggette, R. M., and Brashears, M. L., Jr., 1938, "Groundwater for Air Conditioning on Long Island, New York". U. S. Geological Survey, 413.

Miller, L., and Long, F. M., 1962, "A Practical Approach to Cooling Tower Noise". Heating, Piping, and Air Conditioning, 34, 141-142.

National Association of Corrosion Engineers, 1966, "Cooling Water Treating". NACE, Houston, Texas.

Nelson, J., 1966, "Selecting Materials, Coatings for Water Cooling Towers". Heating, Piping, and Air Conditioning, 38, 109.

Seelbach, H., Jr., and Oran, F. M., 1963, "What to do about Cooling Tower Noise". Sound, 2, 38.

Smith, Maynard E., 1963, "The Use and Misuse of the Atmosphere". Brookhaven Lecture Series, 24, Upton, N. Y.

Stundl, Karl, 1967, "L'Influence Des Centrales Electriques, Sur Le Regime Des Eaux Souterraines, A Proximite Des Rives Des Fleuves". La Tribune du Cebedeau, 20, 74-81.

Thom, C. S., 1969, June 23, Personal Communication.

Thom, C. S., 1969, September 18, Personal Communication.

Van Dam, J. C., 1969, "The Availability of Groundwater for Cooling Purposes". De Ingenieur, A743.

Willa, J., 1966, "Cooling Towers: Step-Children of Industry". Heating, Piping, and Air Conditioning, 58, 153.

CHAPTER XII -1

COMPARISON OF COOLING METHODS

A. Climatic Requirements

Though one frequently sees statements limiting the use of mechanical draft and natural draft towers to certain climatic conditions, these represent, in part, an economic judgment on the part of the writer. For example, McKelvey and Brooke (1959) state, "On the other hand, with a mean wet bulb temperature of 40°F there is not *economic* application at all for mechanically ventilated towers, however low the exhaust heat loading. Canada or countries in North Europe are examples of places where natural draft towers will consequently tend to predominate. With mean wet bulb temperatures of 70°F and over, natural draft towers are not suitable, countries where such temperatures are habitual may therefore require mechanical equipment."

Fluor Corporation's house organ (Fluor-o-scope, Fall 1961) states, "Because of this (air moves in a natural draft tower as a result of a chimney effect created by the difference in density between the moist air inside the shell and the denser air outside), natural draft towers are economically best suited for areas with high humidities, such as Western Europe and part of the eastern and northwestern United States."

It is obvious that more than climatic conditions are involved when these statements are made and assumptions of the cost of labor, materials, power, land, etc., are also factored into the economic decision.

It should also be noted that the temperature of the returned condensate has ramifications in the choice of the condenser and even the turbine itself. We restrict ourselves here to the climatic influence on cooling tower choice.

It should be noted that methods of dissipating heat in both natural draft and mechanical draft wet towers are the same, that is primarily evaporation. Therefore, for wet towers the minimum temperature to which the condensate can be cooled is the wet bulb temperature.

For dry towers, the dry bulb temperature is the minimum temperature to which the condensing water can be cooled.

B. Cooling Tower Operation

Possibly the best review of current operating experience with mechanical draft cooling towers in the United States is that offered by Waselkow (1969) which details 60 years of experience of the Public Service Company of Colorado. Seventy-six percent of Public Service steam generating capability is on cooling towers. Waselkow also presents data on other mountain and southwestern utility companies' experience with cooling towers. He cautions about the difficulties in specifying tower performance since it is so intimately related to weather conditions.

The following figures reflect their experience:

(1) One half to three quarters of a gallon of water consumptively used per kilowatt hour. (For nuclear plant use, 0.9 gallons per kilowatt hour.)

(2) Drift loss is less than 0.1 percent of the circulating water.

(3) Lake cooling is most trouble-free operation, followed by tower operation, and most troublesome is once-through stream flow.

(4) Deterioration of the redwood fill does not follow any consistent pattern.

Natural draft tower experience must be gleaned from European data since only limited American experience is available. Jones (1968a) estimates evaporative losses at 1½% of the circulating flow and drift at less than .2 percent. Blowdown will vary depending upon water quality but should be less than two or three percent of the load even under extreme conditions.

Jones (1968b) also notes that natural draft towers, because of their high initial cost, can only be jusitifed where the cooling demand is extremely great and judges that the smallest individual generating unit which will use natural draft towers will be on the order of 500 megawatts.

Dry towers have much smaller losses. At Rugeley, total makeup has been about 1.5 percent of the boiler feed makeup because of faulty pump glands and cooler leakage (Anon., 1965). Tower makeup of 1.8×10^6 gallons per day is, of course, not required (Christopher, 1965).

It should be noted that if the existing tower is poorly designed, real estate is at a premium and repairs are needed on the existing tower, it may be possible to increase its capacity by as much as 60% (McCann, 1966).

Up to 20% increase in capacity can be gained by newer types of fill material which offer greater surface area. The use of positive pressure sprays can increase capacity by 15%. New designs for drift eliminators can give up to 5% better performance. Up to 10% more capacity can be gained by varying air movement through changes in fan blade angle, and speed and size of mower. A properly designed velocity recovery stack can increase capacity as much as 70%. Partitioning of individual fan cells will help to reduce recirculation.

C. Economic Comparison of Cooling Towers

Can we make an economic comparison of these various alternatives? It is extremely difficult to do so on any objective basis. Jones (1968a) has pointed out that the physical size and cost of an optimum tower for a given size generating unit can differ in cost by a factor of two because of location, fuel costs, load factors, capability penalties and capitalization rates. Because of these, there are wide discrepancies though there have been a fairly large number of comparisons made. They are valid only for the conditions assumed and are not generally applicable.

Possibly the most recent and one of the best was that of Shade and Smith (1969) where they compare six different methods of heat rejection for a modern power plant consisting of two 900 mw units with fossil fired boilers using present day costs. They emphasize that this is only for general comparison, since the costs for any project are greatly influenced by local conditions. The results are shown in Table XII-1.

TABLE XII - 1

ECONOMIC COMPARISON OF COOLING METHODS

Heat Rejection Method	Temperature Rise °F	Inlet Temperature °F	Condenser Back Pressure	Capacity $/Kw
1. Run of river cooling	17	55	1.2	5
2. Bay/lake cooling			1.2	6
3. Natural draft cooling towers - run of river makeup	28	70	1.5, 2.16	7.5
4. Natural draft cooling towers - makeup reservoir			1.5, 2.16	11
5. Cooling pond ($1000 acre)		65		10
6. Dry cooling towers				22

F. A. Ritchings and A. W. Lotz (1963) studied the economics of closed vs. open cooling water cycles and compared a 200 MW_e open cycle and three closed cycle systems for natural and induced draft dry cooling towers, and a mechanical draft fin tube heat exchanger of American design. Results indicate 10% greater investment for closed type systems in comparison to an open cycle wet cooling tower. Annual costs including fixed charges on investment are 10% more. Where water costs are high or where conservation must be practiced, dry towers may be useful.

These were compared against a standard American-made redwood design induced draft tower. The economic optimum was adopted for each type.

These are listed in Table XII-2. The water requirements, land areas, operating costs and annual charges are also listed.

Other broad gauged studies of this type by various consulting firms include that of Steur (1962), who for a 150 MW 1800 psig, 1000/1000F unit at 70% capacity factor gives in Table XII-3 comparative capital costs of the various items needed for different type cooling systems:

TABLE XII-3

EQUIVALENT FUEL COSTS

	River	Lake	Mechanical Draft Cooling Tower	Natural Draft Cooling Tower
Capital Costs, $/Kw	1.0	3.5	3.2	7.2
Typical Fuel Costs to give equivalent annual costs ¢/million BTU	25.0	24.4	24.2	23.5

Weir and Brittain (1962) of still another consulting firm, compare the alternatives of various cooling systems. Though they go through many calculations, they basically make a direct comparison only for induced draft towers and run of river cooling. Surprisingly, for the Mississippi River, water used as cooling, where the bed was constantly changing, the cost of the structure was so great as to overshadow the normal savings in run of river water cooling. In that case, for com-

TABLE XII-2

ECONOMIC COMPARISON OF COOLING TOWERS

	Induced Draft Wet Tower	Natural Draft Wet Tower	Natural Draft Dry Tower	Induced Draft Dry Tower	Mechanical Draft Fin Tube Exchanger
Circulating Water Flow GPM	91,000	95,000	115,000	160,000	95,000
Cooling Range, °F	21	21	17	12	20
Design Approach, °F	20	20	38	33	25
Wet Bath Temperature, °F	65	62	--	--	--
Dry Bath Temperature, °F	--	--	95	95	95
Land Area, Square Feet	18,600	32,000	69,000	22,500	60,000
Total investment cost - millions of dollars	$28,715	$29,580	$31,905	$32,305	$30,980
Back Pressure in. Hg (44% station load)	1.3	1.4	1.5	1.9	1.5
Capability Loss, $1000	105	69	448	430	292
Annual costs plus capability loss, $1000	6,453	6,476	7,217	7,283	6,979

bined total costs, an inland tower to serve two - 160 MW units was $707,000 cheaper than a run of river plant, and $1,529,000 cheaper than a tower at the river site. Rysselberge (1959) compared natural draft vs. mechanical draft towers for a 450 MW plant in the Illinois-Indiana-Ohio area and reached the conclusion that though the first costs of the natural draft tower were 1.25 times the cost of the mechanical draft tower, they were more economical when operating costs were taken into account. Rysselberge maintains that on a cost accounting basis only, capital costs of natural draft towers can exceed mechanically induced draft towers by a factor of 1.6 to 1.7 and still be overall competitive.

Smith and Bovier (1963), showed that for Keystone Station in Western Pennsylvania, though the cooling tower had an economic penalty of $.62/Kw for capital and operating costs, the transmission and fuel cost credits for this nine month plant were so overwhelming, $18.54/Kw, that it not only was the choice but that there was no alternative at that location since sufficient cooling water would not otherwise be available.

Ravet (1963) compared costs for a 400 MW unit for natural draft and induced draft tower for investor owned utilities and publicly owned utilities. The interest charges for the higher initial cost natural draft tower can make an appreciable difference in the yearly costs of a project. For optimum towers with an 18.8°F approach for a natural draft tower and 15°F approach for an induced draft tower, the natural draft tower is $140,000 lower in cost. For public power utility with an approach of 16.5° natural draft and 13.5° induced draft, natural draft has an advantage of $440,000.

It should be noted that the last two economic analyses have been made by Hamon engineers, who have a patented process for consturcting hyperbolic natural draft cooling towers.

Probably the most objective figures are the average prices actually paid for the various types of cooling towers over the past five years. Marly Company, which manufactures both mechanical draft and natural towers, states (Furnish, 1969):

"For mechanical induced draft cooling towers, the average cost per kilowatt of the twelve largest towers purchased in the last five years was $1.67/kilowatt. This cost is a delivered and erected cost but does not include the concrete basin, the electrical controls and wiring for same or the piping external to the tower. This cost figure is a weighted average and the spread can be over twice this figure for smaller stations to somewhat less than this figure for the very large stations. Plant design conditions and design ambient temperatures will also affect the cost.

"For eight large natural draft installations over the last five years, we have an average delivered and erected price of $3.75/kilowatt. This price includes the concrete basin and the cooling tower but does not include piping to the tower. Again, this cost is a weighted average, however, the swing is much narrower."

These average prices do not indicate the costs at a particular site. More important, however, they do not reflect the cost of delivered power since distance to load center and to fuel supply are not represented in the cost figures. Furnish also notes that as of the time of the letter

(February 26, 1969) no dry towers had been sold in their country.

Estimates have been made of the cost of the various types of cooling towers (Kolflat, 1968) and the costs to the year 2000 (Bergstrom, 1968) using conventional wet induced and natural draft technology, and extrapolations for dry cooling towers. The results are shown in Table XII-4.

D. Conclusions

As in many environmental problems, the choice of the proper cooling device is not a simple process, nor is there a unique result. Because of the relationship between condenser, turbine and cooling device, a system analysis study must be done to explore a variety of choices. In addition, the other components of the production of power, transmission, fuel supply, water supply, etc., all play major roles in determining the best choice. One must agree with Jones (1968b), manager of cooling towers for Hamon-Cottrell, who stated, "I am very much against attempting to make statements which indicate the relative costs of various forms of condenser cooling. I have seen studies resulting in numbers which could be used to indicate any conclusion desired." The figures quoted in this chapter, including the comparison of river cooling, show the validity of the above statement. For planning purposes, the average costs of delivered towers, as indicated by Furnish, might best be used.

TABLE XII-4

UNIT AND TOTAL COSTS OF COOLING DEVICES

Cooling Device	Area Required (Normalized)	Water Required Gal/Kw/yr	Additional Unit Costs $/Kw	Cost to year 2000 Billions
OPEN CYCLE		500,000		
POND	500-1000			
MECHANICAL DRAFT				
1. Wet	1 - 2	4000 - 8000	7	11
2, Dry		70	27	
NATURAL DRAFT				
1. Wet	1	4000 - 8000	11	16
2. Dry		70	25	60

E. RESEARCH REQUIRED

The interrelationship of the turbine, condenser and cooling device and their relationship to the geographical location and meteorological conditions make a generalized choice selection methodology impossible. However, it would be useful for a number of typical electric loads, environments, distances to load center, etc., to set up a systems analysis methodology which would detail approximate tradeoffs. For example, how many miles removed from a load center can one be as a function of transmission costs an d tower costs in comparison to run-of-river cooling at nearby site and its attendant thermal pollution costs.

These comparisons are highly dependent upon site conditions and must in essence be made for each site. It might be appropriate to fashion a standardized list of all considerations to be taken into account in such a comparison in order to make such judgments on a more objective basis.

Possibly most useful would be an analysis after the fact of how close to the design criteria did the actual facility operate.

BIBLIOGRAPHY

Anonymous, 1965, "Experience at Rugeley Establishes Design and Use of Dry Cooling Towers". Power Engineering, 69, 62.

Bergstrom, R. N., 1968, "Hydrothermal Effects of Power Stations." Paper presented at American Society of Civil Engineers, Chattanooga, Tennessee.

Christopher, P. J., 1965, "The Dry Cooling Tower System at the Rugeley Power Station of the Central Electricity Generating Board." English Electric Journal, 20, 22-33.

Fluor-o-scope, 1961, Fall, Fluor Corporation, Los Angeles, California.

Furnish, A. G., 1969, February 26 Personal Communication.

Jones, W. J., 1968a,"Natural Draft Cooling Towers." Paper presented at Cooling Tower Institute Meeting.

Jones, W. J., 1968b, July 8 Personal Communication.

Kolflat, R., 1968, statement at hearings before the Senate Subcommittee on Air and Water Pollution of the Committee of Public Works, U. S. Senate, 90th Congress, 2nd Session, 22.

McCann, J., 1966, "Here are Six Ways You Can Increase Cooling Water Capacity". Power, 110, 67-70.

McKelvey, K. K., and Brooke, E. M., 1959, "The Industrial Cooling Tower." Elsevier, Amsterdam, Netherlands.

Ravet, L. C., 1963, "Natural Draft Cooling Towers - Shape of Things to Come". Power Engineering, 50, 67.

Ritchings, F. A., and Lotz, A. W., 1963, "Economics of Closed Versus Open Cooling Water Cycles." Proceedings of the American Power Conference, 416-431.

Rysselberge, J., 1959, "Hyperbolic Towers Deserve Study". Power Engineering, 96, 63.

Shade, W. R., and Smith, A., 1969, "Economics of Cooling Water Use." Engineering Aspects of Thermal Pollution, ed., Parker, F. L., and Krenkel, P. A., Vanderbilt University Press.

Smith, Alexander F. III, and Bovier, Ralph E., 1963, "Hyperbolic Cooling Towers with Reservoir Storage of Makeup to Serve the Proposed Keystone Generating Station." Proceedings of the American Power Conference, XXV, 406-415.

Steur, W. R., 1962, "Artificial Cooling Can Broaden Choice of Sites for Today's New Steam Stations." Electrical World, 157, 42.

Waselkow, C., 1969, "Design and Operation of Cooling Towers". Engineering Aspects of Thermal Pollution, ed., Parker, F. L., and Krenkel, P. A., Vanderbilt University Press, Nashville, Tennessee.

Weir, George E., and Brittain, James F., 1962, "Economic Features in the Selection of Circulating Water Supplies for Electric Generating Stations." American Power Conference, Chicago, Illinois.

LITERATURE REVIEW

EFFECTS OF TEMPERATURE ON PACIFIC SALMON

Introduction

Pacific salmon (Oncorhynchus spp.) are unique in several ways: 1) they provide the most important commercial fin-fishery in the United States, in addition to an invaluable sport fishery; 2) they migrate between the ocean and their natal stream where they spawn only once before death; and 3) they are cold water stenothermal fishes, and hence thermal pollution presents a greater threat to salmon than possibly any other fishes. For these reasons, and because projected power requirements will necessitate steam-electric stations, thermal pollution presents a particularly urgent problem in the Pacific Northwest.

Temperature effects on each life stage (egg, fry, fingerling, yearling and adult) were considered individually for the five species of Northwestern Pacific salmon (sockeye, chinook, coho, pink and chum). General data were included in the first section under Oncorhynchus. Particular emphasis was given to the following subject categories: 1) lethal and optimum temperatures and the effects (lethal and sub-lethal) of temperature on reproduction and development; 2) movement and activity (including migration); 3) feeding and growth; 4) compound stress (changes in conjunction with limiting conditions such as oxygen); 5) acclimation; 6) disease; and 7) physiological responses more or less at the cellular level.

Whenever ambient temperature was reported, its equivalent in degrees Celsius or Fahrenheit was added in parenthesis.

Pacific Salmon - Oncorhynchus

A. Thermal Tolerance

The principles involved in the thermal requirements of fishes were described by Brett (1956). The fundamental requirement is an external temperature that is best suited for internal tissues. Other important principles emphasizing the multiple role of temperature are that warm water fishes generally have a higher level of thermal tolerance than those which inhabit cold water; lethal levels are very important in setting geographical distribution; performance is best in the region of preferred temperature; and a sensitivity to small temperature gradients may also act as a directive factor.

Temperature can be a lethal, a loading, or an inhibiting stress to salmon (Brett, 1958). Beyond the thermal tolerance zone is a high stress area that causes rapid death to salmon exposed to such extremes. Within the thermal tolerance zone, loading stress encloses an area where growth and swimming would be impaired seriously. At still lower temperatures an inhibiting stress level may affect the normal endocrine balance necessary for spawning. While there is no necessary connection between the lethal and optimum temperature of a species, there is, however, a close correspondence between the optimum for activity and the final temperature preferendum (Fry, 1951).

Salmonidae have the least tolerance to high temperatures and their maximum upper lethal temperatures barely exceed 25C (77F) (Brett, 1956). The ultimate lethal levels between salmon and goldfish can differ by as much as 17C (30.6F) (Brett, 1960). Most salmonid eggs suffer when the water temperature goes above 55F (12.8C) or below 35F (1.7C), but the tolerance level of later stages in most species falls to 32F (0.0C) (Royce, 1959).

Salmonid fish have a temperature tolerance zone that falls between 38 and 65F (3.3 and 18.3C). Lethal zones for some species exist from about 55 to 77F (12.8 to 25.0C) and from 35 to 32F (1.7 to 0.0C) (Brett, 1960). Davis (1961) stressed that salmonids require water between 45 and 55F (7.7 to 12.8C). The preferable temperatures are 48 to 52F (8.9 to 11.1C).

B. Acclimation

Temperature changes require continuous acclimation while governing the scope for the metabolic rate (Brett, 1956). Temperature tolerance also depends on acclimation (Brett, 1957). There is no single end point so high and low temperatures can be lethal to young salmon over a range of about 21.5 to 25C (70.7 to 77F) and 7 to -0.1C (44.6 to 31.8F), depending on the species and acclimation.

Temperature, if acting alone, can determine the distribution of fish in laboratory apparatus (Ferguson, 1958). Factors which interfered with temperature responses included light, feeding routines and social behavior. The level of thermal acclimation influenced the range of preferred temperatures. The preferred temperature was higher than the acclimation temperature at low thermal acclimations, but this difference decreased to a final preferendum where both coincided. Each species had a characteristic relationship between the final preferendum and acclimation temperature. Fisher and Scott (1942) concluded that fingerling salmon exhibited their greatest response to a given stimulus when held at their preferred temperature and that this response pattern governs temperature selection.

C. Early Development

The rate of development and time of emergence of young salmon is strongly dependent upon the temperature during development (Hoar, 1958). Some relationships of temperature and development in young salmon were discussed by Burrows (1963). At higher temperatures the growth rate is accelerated, but the size of the fish produced is reduced, primarily due to higher maintenance requirements. Larger emergent fry have a better chance of survival. Emergence time, which is affected by temperature, is important because through acceleration or deceleration of emergence, fish could be placed in an unfavorable environment either from the standpoint of predator activity or available food.

D. Migratory Relationships

Optimum water temperatures for salmonid migration in the Northwest was suggested to range from 45 to 60F (7.7 to 15.6C) (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Burrows (1963) also cited these temperatures as best for the upstream migration of salmon. The peak of the seaward migration of juvenile salmon was reported to occur regularly at temperatures of 10C (50F) or lower (Keenleyside and Hoar, 1954).

Temperature was not believed to play a primary role in the timing of migrations (Hoar, 1958). Juvenile salmon migration is caused primarily by increased thyroid activity according to a hypothesis by Baggerman (1959). External factors, including increased photoperiod and temperature, act along with other intrinsic factors to induce a preference for seawater and a disposition to migrate. It was emphasized that migration is probably not induced by any one factor, but is a result of interaction between a number of factors.

Water temperature also controls the activity of fish predators; hence it influences degree of predation encountered by salmon fingerlings (Burrows, 1963). The preferred or optimum temperatures of both the migrant and the predator influence migrant survival; warmer temperatures generally favor predation.

E. Oxygen Relationships

The decreased solubility of oxygen at increased temperatures was discussed by Shaw (1946). His studies stressed the markedly increased oxygen consumption by salmon and trout at higher temperatures. Normal consumption increased 400 percent from 45 to 68F (7.7 to 20C). Leitritz (1962) emphasized that a rise in temperature, as well as activity and feeding, will increase the oxygen requirements in salmon.

F. Diseases

Most fish diseases are favored by increased water temperatures (Davis, 1961). While higher water temperatures drastically increase the effects of kidney diseases, furunculosis, vibrio disease and columnaris disease in young salmon (Ordal and Pacha, 1963), constant water temperatures are also conducive to disease development (Burrows, 1963).

The causative agent for columnaris disease, Chondrococcus columnaris, ordinarily attacks fish at comparatively high temperatures (Davis, 1961). The optimum temperatures for growth of C. columnaris have been given as 25 to 31C (77 to 87.8F), and although it will grow at much lower temperatures, it is rarely injurious at temperatures below 15C (59F) (Garnjobst, 1945). Borg (1948) stated that the disease progressed rapidly and produced recognizable lesions when the temperature was above 18C (64F).

An average water temperature below 50F (10C) was believed by Fish (1944) to represent the optimum for tissue repair and also to adversely affect the growth of columnaris disease. He showed that the mortality to prespawning injured salmon could be kept to a minimum by retaining the fish in an average water temperature not exceeding 50F (10C). Davis (1961) believed that infections were most likely to occur at water temperatures above 70F (21.1C) among fish that have been handled or otherwise injured.

The major damage by columnaris disease to Columbia River salmon was believed by Ordal and Pacha (1963) to occur to juvenile, rather than adult fishes. These authors suggested that high-virulence strains of C. columnaris in the Columbia River Basin might be due to increased multiplication, hence increased likelihood of mutation, as a result of higher water temperatures.

Field observations have confirmed that conditions at fish ladders can be important factors in the incidence of columnaris disease (Fujihara and Olson, 1962). These present important sites for repetitive columnaris exposure and infection of salmonid fish (Fujihara, 1967). Maximum contamination of fish ladders with columnaris organisms occurs during periods of crowding and highest temperature at peak passage time of anadromous fish. These fish are exposed repeatedly at each dam site and this exposure may constitute a major fector for spreading the disease throughout the river system. In addition, scrap fish that inhabit the ladders may act as a reservoir of the disease.

Furunculosis disease affects chiefly the salmonid fishes (Davis, 1961). These pathogenic bacteria grow best at comparatively low temperatures with an optimum at 10 to 15C (50 to 59F). The disease is likely to reoccur at a hatchery if the temperature of the water is raised above the optimum. Borg (1948) isolated Cytophaga psychrophila, the causative agent for "cold-water disease." This disease is found at low water temperatures and disappears at 55F (12.8C). Fungal infection by Saprolegnia sp. causes mortality chiefly by secondary infection in previously injured or debilitated fish; mortality was delayed when holding ponds were kept at temperatures below 58 to 65F (14.4 to 18.3C) (Fish, 1944). Ceratomyxa sp. was reported to be most virulent to Columbia River salmon when water temperatures approached 65F (18.3C) (Snyder, 1968).

"Gas-bubble disease" occurs in the Columbia River when the water becomes supersaturated with nitrogen. During the spring and summer runoff period, large amounts of water plunge over the spillways, entrapping and dissolving excessive amounts of air. This water can initiate the formation of gas bubbles in the blood and tissues of salmonids resulting in death (Davis and Snyder, 1967; Snyder, 1968a). Thermal additions would increase the seriousness of the existing problem.

G. Thermal Electric Power Development

Aspects of thermal power development that endanger Columbia River salmon have been discussed by Davis and Snyder (1967). Projected thermal electric development could raise temperatures well above 75F (23.9C) during hot weather and periods of low flow. They emphasized that the salmonids would suffer direct mortality from constant or fluctuating temperatures above 75F (23.9C) and that indirect mortalities would result if an environment was created that favored their competitors, predators and disease organisms, and not their food organisms.

An excellent analysis and review of thermal plant and thermal pollution problems and their relationships with salmonid fish in the Columbia River and the Pacific Northwest was provided by Snyder (1968a). Delayed migrations, nitrogen gas effects, and effects on predators, competitors and diseases were among the problems that were emphasized. The problem of how temperature increases can be compounded by low flows and tidal fluctuations was discussed by Snyder (1968b). Tidal action causes flow reversal in the lower Columbia where thermal power plants are planned. This could force juvenile migrants to move prematurely from the estuary into cooler ocean water. Juvenile salmon also could be subjected to a 20F (11.1C) thermal shock if they are passed through thermal electric plant cooling condensers. While the fish may not be killed directly by a 20F (11.1C) increase at low river temperatures, this increase could be fatal when the river temperatures are approaching 70F (21.1C).

Sockeye Salmon - Oncorhynchus nerka (Walbaum)

The sockeye salmon range from southern Oregon to the Bering Sea and enter their spawning streams, which are normally fed by lakes, in the summer and early fall. They may spawn downstream from the lake or at the lake shore itself, but most often spawning occurs upstream from the lake. The fry hatch in the following spring. Some sockeye spend from one to three years in the lake before migrating to the sea, while others finish their life cycle in the lake. The salmon that migrate to the ocean spend from two to five years in that environment before returning to their spawning streams as mature adults. The adults die shortly after one spawning.

A. Eggs

In some of the early work on temperature tolerances to sockeye eggs, Rucker (1937) considered a temperature of 17C (62.6F) too high for egg development. He showed that eggs incubated at higher temperatures grew faster and gave rise to larger embryos in a shorter time than eggs incubated at colder temperatures. Maximum growth increments at 10.7C (51.3F) occurred in 78 days, while at 14.3C (57.7F), the time decreased to 56 days. The temperature thresholds for the normal development of sockeye eggs were defined later by Combs and Burrows (1957) as 42.5F (5.6C) and 55F (12.8C). Combs (1965) found that sockeye eggs were more tolerant to low temperature and less resistant to high temperature than chinook eggs. He also reported that water temperatures below 42.5F (5.6C) at the time of egg deposition produced progressively greater egg mortalities with a decrease in temperature until up to 50 percent were lost at 35F (1.7C). After the 128-cell stage was reached, the eggs tolerated 35F (1.7C).

The viability of eggs and sperm from parents affected with temperature-related columnaris disease was tested by Robins (1964). When both parents were diseased, only 14 percent of the eggs survived. When both parents were healthy, there was 94 percent survival.

B. Fry

Rearing temperatures for young sockeye salmon in some waterways in the Columbia River Basin ranged from 32 to 70F (0.0C to 21.1C) (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967).

When sockeye salmon fry were forced to swim against a current, a sharp rise in temperature of 4 or 5C (7.2 to 9F) did not induce a change in swimming direction (Keenleyside and Hoar, 1954). This was in contrast to the results obtained for chum and coho fry.

The influence of varying temperatures, both in the light and dark, upon the retina of sockeye fry was studied by Ali (1960) to establish a possible correlation between this tissue, temperature and migratory behavior. Temperature had no effect on the cones in the light or dark from 3 to 23C (37.4 to 73.4F). However, in darkness, at 23C (73.4F) the pigment layers of the retina expanded slightly.

C. Fingerlings

Sockeye fingerlings were tested for temperature tolerance by Brett (1952). At an acclimation temperature of 20C (68F), the upper lethal temperature was 24.4C (76.7F). The lower lethal temperature was 6.7C (44F) for acclimation at 23C (73.4F). Sockeye fingerlings were less tolerant than chinook and coho and more tolerant than pink and chum to prolonged high temperature. The region of greatest preference was 12 to 14C (53.6 to 57.2F). Low lethal temperature tests on sockeye fingerlings by Brett and Alderdice (1958) revealed no tolerance to temperatures of -0.5C (31.1F) and lower. The mean resistance times indicated that a temperature of -0.1C (31.8F) approximated the ultimate lower lethal temperatures for young Pacific salmon.

The capacity of sockeye fingerlings to remain active in the zone of thermal resistance was analyzed by Brett (1967). He concluded that 15C (59F) was physiologically ideal for swimming activity. Temperatures of 5 and 24.5C (41 and 76.1F) restricted the swimming performance of fingerlings acclimated to 15C (59F) water. Temperatures above the lethal level caused a rapid decline in swimming ability approaching the extinction point at 27.5C (81.5F).

The metabolic rate of young sockeye salmon increased by more than 50 percent when they were subjected to a temperature change of 10 to 15C (18 to 27F) while swimming at a speed of one foot per second (Fisheries Research Board of Canada, 1962).

The growth, mortality and food conversion in sockeye fingerlings and their relationships to temperature variations found in lakes were analyzed by Donaldson and Foster (1941). The fingerlings refused to eat and mortality was high at temperatures above 70F (21.1C). Fingerlings which were held at 48 to 50F (8.9 to 10C) exhibited maximum growth, best food utilization and lowest mortality.

Temperature effects on the pathogenicity of columnaris disease in sockeye fingerlings were studied by Fish and Rucker (1945). Temperatures below 55F (12.8C) inhibited the growth of the disease; at temperatures above 70F (21.1C) it became extremely virulent. The causative organism presumably becomes increasingly pathogenic at temperatures between these thresholds.

D. Yearlings

Juvenile sockeye salmon, in some Columbia River Basin waterways, migrated downstream at water temperatures ranging from 34 to 64F (1.1 to 17.8C) (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Peak runs of sockeye smolts in the Lower Babine River in British Columbia occurred at temperatures between 7.7 to 9.2C (45 to 49F) (Withler, 1952). The peak migration of sockeye smolts corresponded to average weekly temperatures of 42F (5.6C), 44F (6.7C) and 47F (8.3C) from May to June in Frazer Lake in Alaska (Eaton, 1968). Sockeye began their downstream migration at approximately 40F (4.4C) in the Wenatchee River system in Washington. Most of the migration occurred from 43 to 45 F (6.1 to 7.7C) (French and Wahle, 1959). Increasing surface temperatures above 12 to 14C (53.6 to 57.2F) in the southern lakes of British Columbia were correlated with the termination of sockeye migration (Brett, Hollands, and Alderdice, 1958).

Sockeye smolt migrations in southwestern Alaska were discussed by Hartman, Heard and Drucker (1967). Most migrations started in the spring when the water temperatures approached 40F (4.4C) and were virtually over when the temperature neared 50F (10C). Similar observations were reported by Parker and Vincent (1955) in an Alaskan lake where the migrations started when the water temperature reached about 40F (4.4C) and stopped at 55F (12.8C). According to Foerster (1937), the migration of young sockeye downstream from a lake in British Columbia seemed to be entirely due to a threshold migration temperature from 4.5 to 5.5C (40.1 to 41.7F). The migration did not seem to be related to the rate of change of temperature. A high "temperature blanket" formed on the lake and seemed to inhibit some of the young sockeyes from migrating until the next spring. In some Russian rivers, the greatest downstream migration of young sockeye corresponded with a sharp drop in temperature, pH, dissolved oxygen concentration and an increase in carbon dioxide (Krogius, 1959).

Oxygen consumption among yearling sockeye was determined by Brett (1964) for various swimming speeds at temperatures from 5 to 24C (41 to 75.2F). A logarithmic increase in oxygen demand with increased swimming speeds characterized each acclimation temperature. The standard metabolic rate was about five and one-half times greater at 24C (75.2F) than at 5C (41F). The effect of temperature was greatest on sustained speeds and least on burst speeds.

Water velocity for safeguarding sockeye under-yearlings at dams was discussed by Brett, Hollands and Alderdice (1958). The optimum cruising speed for yearling sockeye occurred at 15C (59F). Maximum sustained speeds were generally between 1.0 and 1.5 feet per second. If the approach velocities above dams exceed 1.0 feet per second, the fish may not be able to resist them since their capacity to do so for more than an hour is dependent upon maintenance of a temperature between 12.5 and 17.5C (54.5 and 63.5F). Brett (1957) also emphasized that correlation of highest cruising speeds and temperatures has provided an index of the temperature at which fish are most likely to succeed and an indication of the temperature at which they are most likely to be found. Young sockeye also have a greater ability to perform at low temperatures than do young coho salmon.

E. Adults

High temperature mortality of adult sockeye salmon was reported by Fish (1944). Forty-nine percent of the sockeye held at an average temperature of 60.8F (16.0C), ranging from 49 to 74F (9.4 to 23.3C), died after 48 days. Only four percent died after being held from 58 to 61 days at an average temperature of 53.4F (11.9C), ranging from 52 to 60F (11.1 to 15.6C).

Sockeye salmon spawned at temperatures ranging from 42 to 62F (5.6 to 16.7C) in some waterways in the Columbia River Basin (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Royal (1953) reported that sockeye spawned in two British Columbia tributaries from 45 to 55F (7.7 to 12.8C) with peak spawning at 50F (10C). He concluded that water temperature was one of the major limiting factors in the timing of spawning. Russian studies indicated that certain sockeye spawning sites in rivers ranged from 2.79 to 4.53C (37 to 40.2F), while some lake spawning sites exhibited more variance, ranging from 0.1 to 20.5C (32.3 to 68.9F) (Krokhin, 1960).

Temperature was reported to be secondary to light in its effect upon sockeye sexual maturation (Combs, Burrows and Bigej, 1959; Progressive Fish Culturist, 1958). The authors believed the results to be applicable to other species of salmon.

Adult sockeye migrations occurred at temperatures from 40 to 74F (4.4 to 23.3C) in some Columbia River Basin waterways (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Krogius and Krokhin (1958) reported that instead of following a positive temperature gradient when migrating upstream, adult sockeye in a Russian stream followed a negative gradient caused by an intensive upstream snow melt. This was believed to be a direct factor in the start of upstream migration.

In an early study on factors controlling migration and spawning of sockeye salmon, Ward (1921) believed that sockeye choose the stream with the lower temperature, if a choice is available.

High water temperature has been a major cause of migration delay among adult sockeye as shown by studies on the Okanogan River, a Columbia River tributary (Major and Mighell, 1966). Above 70F (21.1C), rising or stable Okanogan River temperatures blocked the entry of fish from the Columbia River. Falling temperatures allowed the migration to continue. The authors emphasized that such delays can reduce survival because they expose the sockeye to other factors that affect them adversely. An earlier contrasting study by Chapman (1941) indicated that when the temperatures of the Okanogan River ranged from 4 to 12F (2.2 to 6.7C) higher than temperatures in the Columbia River, the normal migration of adult sockeye took place.

Temperature-growth relationships were discussed by Burrows (1963). Sockeye salmon grew faster at all temperatures between 40 and 60F (4.4 and 15.6C) than did chinook salmon. A ten degree rise in temperature between those two values also increased food consumption by 45 percent in sockeye.

Columnaris disease was cited as one of the major factors contributing to the decline of sockeye salmon runs in the Columbia River Basin (Ordal and Pacha, 1963). Burrows (1960) emphasized that 60F (15.6C) is the critical temperature for disease development in the adult sockeye.

Columnaris disease was widespread among adult sockeye in certain Fraser River, B.C., spawning areas (Colgrove and Wood, 1966). A temperature above 60F (15.6C) was concluded to be necessary to initiate the pathological effects of the disease. The disease seldom occurred at temperatures below 55F (12.8C). Pre-spawning losses of sockeye in the Fraser watershed in three dominant cycle runs were estimated at $8,000,000 to $15,000,000.

High temperature extremes in British Columbia have affected sockeye females in some Fraser River tributaries (International Pacific Salmon Fisheries Commission, 1962). When the temperatures at the spawning sites reached 72F (21.7C), 5 to 86 percent of the females died without spawning. The actual cause of mortality was a bacterial infection of the gills brought on by high temperatures.

Water temperatures were abnormally high in the summer of 1941, averaging 68.5F (20.3C) and reaching a record high of 74.5F (23.6C), and this was stated to be the plausible cause of the low number of sockeye adults reaching Rock Island Dam on the Columbia River (Fish, 1948). The salmon were turning into lower Columbia River tributaries, apparently seeking relief from the high water temperatures. Columnaris disease was assumed to have caused a great mortality at this time due to the high water temperature.

In studies of migrating adult sockeye and columnaris disease, Fujihara (1968) noted large numbers of exposed and infected fish which survived to spawn. He suggested that columnaris exposure and the development of high agglutinating titers may have protected these fish from columnaris-induced mortality during migration.

Chinook Salmon - *Oncorhynchus tshawytsha* (Walbaum)

Chinook salmon range from southern California to the Bering Sea. There are three races of chinook in the Columbia River and two races in many other rivers entering from February to June (spring); June to July (summer); and August to December (fall). All races spawn in the fall, the exact time depending upon the race and location. While some races migrate downstream shortly after emerging from the gravel, other faces may stay in fresh water up to 15 months. The chinooks remain in the ocean from three to seven years before returning to the parent stream to spawn. The adults die shortly after one spawning.

A. Eggs

The temperature range for the normal development of chinook salmon eggs is 42.5F (5.8C) to 57.5F (14.1C) (Burrows, 1954; Combs and Burrows, 1957). When water temperatures were below 42.5F (5.8C) at the time of egg deposition, Combs (1965) found progressively greater mortalities with a decrease in temperature down to 35F (1.7C) when the egg losses were almost complete. After the 128-cell stage the eggs tolerated 35F (1.7C). Leitritz (1962) stated that water temperatures above 56F (10.3C) adversely affect egg development in chinook salmon.

The tolerance of chinook eggs to temperature exposure varies with the stage of development. Donaldson (1954) and the Washington State Department of Fisheries (1960) reported the greatest percentage of mortalities occurred at the time prior to closure of the blastopore and during the period just previous to and during hatching. The results generally indicated that as the temperature increased, the time necessary to kill a given percentage of the eggs decreased.

Water temperatures that could be harmful to the development of chinook salmon eggs are indicated by the range of incubation temperatures reported for some Columbia River Basin waterways (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). These temperatures ranged from 32 to 64F (0.0 to 17.8C) for spring chinook and from 32 to 66F (0.0 to 18.9C) for summer chinook.

Temperature increments exceeding 4F (2.2C) above the Columbia River base temperature, which did not exceed 57F (13.9C), caused excessive mortality in an October spawn of chinook salmon, but the December spawn tolerated a 12F (6.7C) increment without significant mortality (Olson, 1967a; Olson and Nakatani, 1968). The results indicated that some heat could be added during the winter without significant detrimental effect to the eggs.

Significant mortality occurred in a group of chinook salmon eggs incubated at temperatures 8F (4.4C) higher than the seasonal trend of the Columbia River; this ranged from 36 to 57F (2.2 to 13.9C) (Olson and Foster, 1957). Apparently there was a lasting adverse effect of high temperature; although 90 percent of the eggs hatched successfully, the fry and fingerlings suffered heavy mortalities even though the mean temperature of this lot was below 50F (10C) in the fingerling stage.

Chinook salmon eggs incubated in Dorena Reservoir, Oregon, at temperatures over 60F (15.6C) suffered excessive mortality (Johnson and Brice, 1953). Chinook salmon from the Green River, Washington, were reared from fertilization for 46 weeks at various constant temperatures. Egg mortality averaged five percent at 57.5F (14.1C) but increased to 100 percent at temperatures above 62.5F (17.2C) (Seymour, 1954). Winter-run chinook eggs in the Sacramento River system had a monthly mortality rate of 97.6 percent at an average water temperature of 63.3F (17.3C) and only 2.8 percent at an average water temperature of 45.7F (7.2C) (Slater, 1963). Studies of a Sacramento River tributary revealed that fluctuating temperatures from 42 to 52F (5.0 to 10.6C) were not harmful to chinook salmon eggs (Gangmark and Broad, 1955).

Mazuranich and Neilson (1959) reported that temperature extremes of 33 and 68F (0.6 and 20C) had no apparent effect on the development of white-spot disease (coagulated-yolk disease) in eyed chinook salmon eggs. They suggested that advanced eggs are more resistant to the shock of abrupt temperatures than immature eggs.

B. Fry

Rearing temperatures for chinook salmon in some Columbia River Basin waterways ranged from 32 to 70F (0.0 to 21.1C) for spring chinook and from 32 to 77F (0.0 to 25.0C) for summer chinook (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). When chinook fry are beginning to feed, they are less tolerant to high temperature exposure than later (Donaldson, 1954; Washington State Department of Fisheries, 1960).

Relationships between increased temperature and growth of chinook fry were observed in laboratory experiments; a 2F (1.1C) increase in temperature increased body weight by a factor of 1.4 (Olson, 1967a; Olson and Nakatani, 1968).

C. Fingerlings

Chinook salmon fingerlings were tested for temperature tolerance by Brett (1952). At an acclimation temperature of 20C (68F) the upper lethal temperature was 25C (77F). The lower lethal temperature was 7.4C (45.3F) for fish acclimated at 23C (73.4F). Chinook fingerlings were more tolerant to prolonged high temperatures than sockeye, pink and chum fingerlings, but exhibited only slightly more tolerance than cohos. The region of greatest preference was 12 to 14C (53.6 to 57.2F).

First-feeding chinook fingerlings did not develop normally when reared at temperatures above 55F (12.8C) (Burrows, 1954). Rearing temperatures for chinook fingerlings in some Columbia River Basin waterways ranged from 32 to 70F (0.0 to 21.1C) for spring chinook and from 32 to 77F (0.0 to 25C) for summer chinook (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967).

Temperature categories have been determined by Junge and Phinney (1963) regarding releases of chinook fingerlings into the Columbia River from the Spring Creek Hatchery. The categories were: Ideal, 46 ± 3F (7.8 ± 1.7C); Safe, 40-42F (4.4-5.6C); and Critical, less than 40F (4.4C) and more than 52F (11.1C). The constant temperature of 46F (7.8C) at the hatchery was believed important in determining the eventual survival of the fish.

Racial differences influence thermal tolerance according to Dean and Coutant (1968). Columbia River fall-run chinook were more sensitive than British Columbia spring-run chinook.

The acute lethal temperature was reported to be a function of the immediate thermal history and was affected little by the developmental temperature regime (Coutant and Dean, 1967; Dean and Coutant, 1968). Columbia River chinook salmon were reared from eggs to fry at various temperatures above the normal seasonal cycle, and the young fish did not become significantly more tolerant to high temperatures. Therefore, raising hatchery stocks at slightly elevated temperatures would not aid the fish in overcoming thermal stress, such as passing heated discharges, except that to be expected from the immediately previous thermal history.

The relationship of temperature to meristic characters in chinook salmon was investigated by Seymour (1959). The average number of vertebrae was lowest at rearing temperatures in the middle portion of the 39 to 62F (3.9 to 16.7C) range than for lots reared at either extreme of the range. However, the opposite effect was observed in counts of rays in the anal and dorsal fin.

Growth and temperature relationships were reported by Seymour (1954) in Green River, Washington, chinook salmon reared at various constant temperatures from fertilization for 46 weeks. The resulting average weight per fish was 0.0072 lbs. at 45F (7.7C) and 0.040 lbs. at 55F (12.8C).

Dietary protein requirements for chinook fingerlings are dependent upon the water temperature (Delong, Halver and Mertz, 1958). Optimum growth at 47F (8.3C) required 40 percent protein, whereas 55 percent protein was required at 58F (14.4C). Threonine requirements were not altered (0.9 percent dry ration) at 8C (46.4F) and 15C (59F) when chinook fingerlings were fed a diet of 40 percent crude protein (Delong, Halver and Mertz, 1962).

Sustained swimming speeds of chinook fingerlings were lowered by reduced oxygen and temperature (Davis et al., 1963). A slight reduction in dissolved oxygen from saturation levels usually reduced the sustained swimming speed. Fingerlings performed better at 20C (68F) than at 10C (50F) at all dissolved oxygen concentrations. Chinook fingerlings did not perform as well as coho fingerlings in the same test.

Chinook living in nuclear reactor effluents were studied by Olson (1967b). Differences in mortality, growth and radionuclide incorporation were attributable only to temperature effects and stage of development of the fish. No marked racial differences were found from stock from Puget Sound or Priest Rapids, WAshington.

Columnaris disease in chinook fingerlings raised in Dorena Reservoir, Oregon, was discussed by Johnson and Brice (1952). No lesions of the disease were noted when the water stayed below 55F (12.8C). Low disease mortality was noted at temperatures near 60F (15.6C). High mortality occurred at 60 to 70F (15.6 to 21.1C) and higher. The survival of chinook fingerlings following exposure to water containing columnaris organisms was found to be inversely related to the concentration of the organisms, the length of exposure, and temperature (Fujihara, Olson and Foster, 1960). Further experiments by Olson and Fujihara (1963) showed that increased age and not size of the fish was more important to the increasing resistance to columnaris disease.

"Gas-bubble disease" among chinook fingerlings was diagnosed by Pauley and Nakatani (1967) and thought to have been caused by supersaturation of oxygen or nitrogen in the water. The sumptoms included swollen gill filaments that commonly contained hemolyzed red blood cells, and a thickening of the roof of the mouth; the latter was thought to be a unique early symptom of the disease.

Sacramento River chinook disease has been related to temperature by Ross, Pelnar, and Rucker (1960) and Parisot and Pelnar (1962). The infectious agent, perhaps a virus, seems to be specific for chinook salmon. The disease has not been recognized in wild populations, but is suspected of depleting natural stocks. A temperature of 46 to 48F (7.8 to 8.9C) is the probable triggering agent. Optimum temperature for the disease is about 50F (10.0C). Temperatures of 54F (12.2C) will inhibit the disease while temperatures over 55F (12.8C) will control the epizootic.

D. Yearlings

Migrations of juvenile spring and summer chinook occurred at temperatures from 32 to 68F (0 to 20C) in some Columbia River Basin tributaries (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Chinook in the Wenatchee River system began their downstream migration at approximately 40F (4.4C); the major part of the migration occurred from 43 to 45F (6.1 to 7.7C) (French and Wahle, 1959).

Shasta Dam on the Sacramento River in California and its subsequent effects on the chinook salmon were discussed by Moffett (1949). The construction of the dam was influential in maintaining higher winter temperatures in the Sacramento River long after natural conditions would have cooled the stream. This accelerated the incubation of the eggs following deposition and advanced the time of seaward migration. It was considered an advantage as far as the river life of the young salmon was concerned because it gave a greater time for migration. These improvements were believed to compensate for the loss of spawning grounds above Shasta Dam. A later effect of the dam was to create a temperature regime favorable to the development of a winter race of chinook (Slater, 1963).

Acute temperature increases caused rapid death to yearling chinook at test temperatures between 85 and 90F (29.4 and 32.2C) (Snyder, 1968a). These increases of 35 to 40F (19.4 to 22.2C) approximated the levels typical of a nuclear reactor discharge plume in the Columbia River. The results indicated temperature increases of 35 to 40F (19.4 to 22.2C) are lethal when the river is at 50F (10C), that increases of 25 to 30F (13.8 to 16.6C) are lethal at a river temperature of 60F (15.6C) and that increases of 15 to 20F (8.3 to 11.1C) are probably lethal when the river is at 70F (21.1C).

E. Adults

Higher holding temperatures increased the mortality of adult chinook salmon (Fish, 1944). Sixty-four percent of the chinooks held at an average temperature of 60.8F (16.0C), ranging from 49 to 74F (9.4 to 23.3C), died after 56 days. Only 25 percent were lost after being held from 58 to 61 days at an average temperature of 53.4F (11.9C), ranging from 52 to 60F (11.1 to 15.6C). Colder holding water had a detrimental effect on spawning fall chinooks (Reingold, 1968). When the fish were removed from the Snake River, Idaho, which ranged from 54 to 64F (12.2 to 17.8C), and held for 51 days in colder Rapid River water, which ranged from 38 to 48F (3.3 to 8.9C), approximately one-third of the adults died and about one-fourth of the eggs had not ripened.

Spawning temperatures in some Columbia River Basin waterways ranged from 47 to 66F (8.3 to 18.9C) for summer chinook and from 36 to 65F (2.2 to 18.3C) for spring chinook (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Chinook salmon spawned in Prairie Creek, California, at midday temperatures of 48 to 51F (8.9 to 10.6C) (Briggs, 1953). Burrows (1960) confirmed the speculation that low temperatures may inhibit the normal endocrine balance necessary for spawning. He reported that an exotic race of chinook salmon did not spawn when the temperature dropped below 40F (4.4C).

Relationships between temperature, feeding and growth rates in chinook salmon were discussed by Burrows (1963). A ten degree rise between 40 and 60F (4. 4 and 15.6C) increased food consumption by 60 percent. Chinook salmon grew more rapidly with temperature increases than did sockeye salmon.

Adult migration temperatures in some Columbia River Basin waterways ranged from 40 to 68F (4.4 to 20.0C) for spring chinook, from 51 to 77F (10.6 to 25.0C) for summer chinook, and from 40 to 56F (4.4 to 13.3C) for fall chinook (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967).

The migration paths of adult summer chinook were determined in the Columbia River near the Hanford reactor outfalls (Coutant, 1968). Most of the fish avoided the heated plumes by migrating close to the shoreline.

"Gas-bubble disease" in adult chinook at a hatchery spawning channel was described by Westgard (1964). Injury was manifested by blindness and affected 34 percent of the adult salmon. Nitrogen supersaturation from cascading forebay water was described as the major cause of the outbreak.

Temperature-related columnaris disease was described by Ordal and Pacha (1963) as one of the major factors that has contributed to the decline of chinook salmon runs in the Columbia River Basin. Burrows (1960) stressed that 60F (15.6C) is the critical temperature for the development of this disease in chinook salmon.

Coho Salmon - Oncorhynchus kisutch (Walbaum)

Coho salmon range from northern California to the Bering Sea and enter coastal streams to spawn between September and December. Some may spawn a short distance upstream while others migrate farther into the smaller tributaries. The fry appear in April and usually don't migrate downstream until the spring of their second year. Cohos mature in the ocean and usually return to spawn as three-year-old adults. All adults die shortly after spawning.

A. Eggs

Only a few investigations on coho eggs are evident. The relationship of increased temperature to decreased incubation time in Waddell Creek, California, was discussed by Shapovalov and Taft (1954). Coho eggs incubated at 51.3F (10.7C) hatched in about 38 days, whereas eggs incubated at 48.0F (8.9C) hatched in 48 days. The temperature of advanced near-hatching eggs in some Russian coho nests in January ranged from 2.1 to 5.3C (35.8 to 41.5F) (Gribanov, 1962).

B. Fry

When coho fry were forced to swim against a current, a sharp rise in temperature of 4 or 5C (7.2 to 9F) regularly produced a change in direction (Keenleyside and Hoar, 1954).

Hatchery epizootics of the myxobacterium Cytophaga psychrophila in coho fry and fingerlings are influenced greatly by water temperature (Unpublished research by Earp and Ordal, cited in Rucker, Earp and Ordal, 1953). The disease usually occurs from 40 to 50F (4.4 to

10.0C). Although the disease has sometimes persisted in water at 60F (15.6C), the mortalities usually decline when the temperature reaches 50F (10C) or above.

C. Fingerlings

The temperature tolerance of coho fingerlings has been tested by Brett (1952). When acclimated at 20C (68F), the upper lethal temperature was 25C (77F). The lower lethal temperature was 6.4C (43.5F) for acclimation at 23C (73.4F). Coho fingerlings were more tolerant to prolonged high temperatures than sockeye, pink and chum fingerlings and exhibited about the same tolerance as chinook. The region of greatest preference was 12 to 14C (53.6 to 57.2F).

The peak periods of downstream migration of coho fingerlings in Sand Creek, Oregon, over a three-year period occurred at temperatures of 45.0 to 61.0F (7.7 to 15.6C) (Sumner, 1952).

Sustained swimming speeds of coho fingerlings were lowered by reduced oxygen and temperature (Davis et al., 1963). A slight reduction in dissolved oxygen from saturation levels usually reduced the sustained swimming speed. The fingerlings performed better at 20C (68F) than at 10C (50F) at all dissolved oxygen concentrations. Coho fingerlings also performed better than chinooks in the same test.

High concentrations of free carbon dioxide depressed the final swimming speed of coho fingerlings at 20C (68F) (Dahlberg, Shumway and Doudoroff, 1968). The authors believed the effects would have been greater at a lower test temperature.

The respiratory rate of starved fingerling coho salmon was a function of both water temperature and the physiological condition of the fish, with the latter assuming greater importance as the period of starvation lengthened (Varma, 1950).

Temperature and columnaris disease relationships in coho fingerlings reared in Dorena Reservoir, Oregon, were investigated by Johnson and Brice (1952). Heavy mortality occurred at temperatures from 60 to 70F (15.6 to 21.1C) and higher. No mortality occurred in water near 60F (15.6C) and no lesions were noted when the water stayed below 55F (12.8C).

D. Yearlings

Juvenile coho salmon migrated in a number of Columbia River Basin waterways at temperatures from 40 to 61F (4.4 to 16.1C) (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967).

The highest cruising speeds have provided an index to the temperature at which fish are most likely to succeed and to the temperatures at which they are most likely to be found (Brett, 1957). Young coho salmon exhibited an optimum cruising speed at about 20C (68F) and maintained a high level of performance even approaching the lethal thermal level.

Water velocity for safeguarding coho under-yearlings at dams was discussed by Brett, Hollands, and Alderdice (1958). The optimum cruising speed for yearling coho salmon occurred at 20C (68F). Maximum sustained speeds were generally between 1.0 and 1.5 feet per second. If the approach velocities above dams exceed 1.0 feet per second, the fish may not be able to resist them since their capacity to do so for more than an hour is dependent upon temperatures between 18.5C (65.3F) and 21.5C (68.7F).

Temperature and x-irradiation effects on DNA-synthesis, cell kinetics and structural damage were studied in juvenile coho salmon (Johnson, Conte and Nakatani, 1967). The cell kinetics of the intestinal epithelium and DNA-synthesis were temperature dependent.

Multivariate techniques are important in assessing associated environmental factors. Alderdice (1963) conducted studies on the mean resistance times of juvenile coho salmon acclimated at 12C (53.6F), to 3 mg/l of sodium pentachlorophenate at various combinations of salinity, temperature and dissolved oxygen. A maximum response time was associated with levels of the variables at 17.68 0/00 salinity, 4.86C (40.7F) and 7.66 mg/l of dissolved oxygen.

"Cold-water disease" in young coho salmon is found generally in the spring when water temperatures are low (Ordal and Pacha, 1963). The infectious organism, Cytophaga psychrophila may cause heavy fish losses. The disease is self-limiting, however, and disappears as the water temperature increases. An incidence of the disease persisted in young cohos held at 43F (6.1C). After two days, no additional mortality occurred in a group of the fish placed and held at 55F (12.8C).

E. Adults

The majority of adult coho studies are reports of naturally occurring migration and spawning temperatures. The peak periods of upstream coho migration in Sand Creek, Oregon, occurred at temperatures from 40 to 52F (4.4 to 11.1C) (Sumner, 1952). Allen (1959), in studies of environmental factors, reported that coho salmon runs did not occur until the water temperature dropped below 50F (10C). Coho salmon spawned in various Columbia River Basin waterways at temperatures from 40 to 45F (4.4 to 7.7C) (Snyder et al., 1966, cited in Pacific Northwest Laboratories, 1967). Russian studies revealed that the water temperatures at certain coho spawning grounds ranged from 0.8 to 7.7C (33.4 to 45.3F) throughout the year (Gribanov, 1963).

Borg (1948) related an instance of "gas-bubble disease" in coho salmon. Death was attributed to the release of gas into the tissues from the water which became supersaturated when the temperature was raised.

Pink Salmon - Oncorhynchus gorbuscha (Walbaum)

Ranging from northern California to the Bering Sea, the pink salmon enter their spawning streams mainly in September and October, usually spawning a short distance upstream. The fry, which hatch in February and come out of the gravel in April and May, migrate almost immediately downstream to the ocean. The salmon mature in the ocean and return to spawn in their natal streams as two-year-old adults. All adults die shortly after one spawning.

A. Eggs

Shorter incubation periods for British Columbia pink salmon eggs were the result of increased temperatures (Pritchard, 1944). When the air temperature (which was correlated with the water temperature) was approximately 4.4C (39.9F), the eggs hatched in 247 days; the eggs hatched in 207 to 227 days at 7.8C (46F).

Pink salmon eggs tolerated temperatures as low as 33F (0.6C) for several weeks when the initial incubation temperature was above 42F (5.6C) for a month (Combs and Burrows, 1957). Another study on low temperature relationships showed freezing to be an important cause of mortality to pink salmon eggs when the maximum daytime air temperatures remained below 0.0C (32F) for at least two consecutive days (McNeil, 1966).

Pink salmon spawned naturally and successfully in the intertidal waters of southeastern Alaska (Rockwell, 1956). The eggs survived better in some of these intertidal areas than in upstream locations, and more eggs survived indefinitely at a given concentration of salt water at lower, rather than higher, temperatures. Similar results by Sheridan (1961) also indicated that pink salmon eggs reared in dilute salt water survived better than eggs reared in fresh water. The intertidal areas, which were warmer than the upstream waters, may have protected the eggs from freezing in addition to accelerating growth.

Hydroelectric power developments and large-scale logging of salmon watersheds threaten pink salmon eggs and fry by subjecting them to unfavorable temperatures (Sheridan, 1961).

Egg and sperm viability from pink salmon unaffected and affected with temperature-related columnaris disease was tested by Robins (1964). When both parents were diseased, only 45 percent of the eggs survived; when both parents were healthy, 83 percent of the eggs survived. The eggs wore incubated at a constant 44-45F (6.7-7.7C).

B. Fry

The majority of the pink salmon fry studies are concerned with temperature and migration relationships. Pritchard (1944) reported that small temperature variations had little effect on the migration of pink salmon fry, while Vernon (1958) found that an acceleration of egg and fry development due to warmer temperatures disrupted the timing of seaward migration. He stressed that this could affect survival by placing the fish in unfavorable environmental conditions from the standpoint of available forage, predators, or unfavorable estuarine conditions. Record high water temperatures averaging 61.8F

(16.6C) in the Georgia Strait estuary had a harmful effect on migrating pink salmon fry (International Pacific Salmon Fish Commission, 1962). Snow melt in the spring, along with increasing air temperature, may cause young pink fry to migrate to the sea at an unfavorable time (Sheridan, 1961). Wickett (1960) stated that even though they may have been subjected to quite different incubation temperatures, the majority of pink fry migrate when the stream temperatures are between 4 and 5C (39.2 and 41F).

C. Fingerlings

The temperature tolerance of pink salmon fingerlings was tested by Brett (1952). At an acclimation temperature of 20C (68F) the upper lethal level was 23.9C (75.2F). The pinks were less tolerant to prolonged high temperature than chinook, coho and sockeye salmon fingerlings and had about the same tolerance as chum fingerlings. The region of greatest preference was 12 to 14C (53.6 to 57.2F).

D. Adults

Brett (1960) emphasized that the upper lethal temperature levels between different fish species can differ as much as 17C (30.6F). The lethal temperature of the goldfish Carassius is 41C (105.8F), whereas the pink salmon succumbs at 24C (75.2F).

Upstream migrations of adult pink salmon in McClinton Creek, British Columbia, were correlated to daily rainfall and stream depth (Pritchard, 1936). Temperature was not believed to play a significant role in determining migration time. In most instances Alaskan pink salmon entered and spawned in colder streams earlier in the season than in warmer streams (Sheridan, 1960). This suggested that the coordination of spawning time with later incubation temperature is necessary for the highest survival of a species since deviation from the normal temperature pattern can cause mortality. Abnormal air temperatures were believed to affect adult spawning pink salmon by Sheridan (1961) who compared air and water temperatures in some Alaskan spawning areas.

Prespawning mortalities of pink salmon are normally associated with high water temperatures. The direct cause is sometimes columnaris disease (Robins, 1964).

Chum Salmon - Oncorhynchus keta (Walbaum)

Chum salmon range from northern California to the Bering Sea and enter their spawning streams in the late fall. They usually spawn a short distance upstream, although in the Yukon River system they travel about 2,000 miles. The fry migrate downstream shortly after emerging from the gravel and are not usually found in the streams after July. The chum salmon mature in the ocean for three to four years before they are ready to spawn. All adults die shortly after one spawning.

A. Eggs

The majority of chum salmon egg studies are concerned with lower, rather than upper, lethal temperatures. Rockwell (1956) indicated that more Alaskan chum salmon eggs survive indefinitely at a given concentration of salt water at lower, rather than higher, temperatures.

The lowest optimal temperature for Russian chum salmon egg development was 1.5 to 2.0C (34.7 to 35.6F) (Kanidev and Frolenko, 1966). Normal development was possible at lower temperatures only if it started early enough in the season and if the blood hemoglobin circulation stage was completed before colder temperatures set in.

Freezing was an important cause of mortality to chum salmon eggs when the maximum daytime air temperatures remained below 0.0C (32F) for at least two consecutive days (McNeil, 1966).

"Icing-down" of chum eyed eggs for shipment had no deleterious effect even up to 14 days (Fish and Burrows, 1939). The hatching periods were delayed when the eggs had been iced for more than one week, but this delay had no effect on subsequent development. The growth rate was more dependent on the actual age of the eggs than upon the hatching time.

B. Fry

Low lethal temperature tests on chum salmon fry and fingerlings revealed no tolerance to temperatures of -0.5C (31.1F) and lower. The mean resistance times indicated that a temperature of -0.1C (31.8F) approximated the ultimate lower lethal temperature for young Pacific salmon (Brett and Alderdice, 1958).

Various studies have related chum salmon fry migration and increased temperature. Hoar (1951) found rapidly rising temperatures to increase activity and produce negative rheotaxis. When chum fry were forced to swim against a current, an acute rise in temperature of 4 to 5C (7.2 to 9F) regularly produced a change in direction (Keenleyside and Hoar, 1954). Active swimming with the current, when temperatures rise sharply, was considered a mechanism which hastens or induces downstream movement in chum which have remained past the time of peak migration of the species (Hoar, 1958).

Chum salmon fry acclimated to cold water schooled more strongly than those acclimated to warm water, but this effect was not considered to be statistically significant (Shelbourn, 1966). Hoar (1951) also believed that the intensity of schooling activity did not seem to be affected by temperature.

Water temperature and the numbers of chum salmon fry vertebrae were correlated by Kubo (1950). There were a significantly higher number of vertebrae in fry raised in water from 0.0 to 5.0C (32 to

41F) than in those raised in temperatures from 6.5 to 7.5C (43.7 to 45.5F).

C. Fingerlings

The temperature tolerance of chum fingerlings was tested by Brett (1952). The upper lethal temperature was 23.8C (74.8F) for fish acclimated at 20C (68F). The lower lethal temperature was 7.3C (45.1F) for acclimation at 23C (73.4F). Chum were less tolerant to prolonged high temperature than chinook, coho and sockeye fingerlings and had about the same tolerance as pink fingerlings. The region of greatest preference was 12 to 14C (53.6 to 57.2F).

D. Yearlings

Acute temperature increases caused rapid death to yearling chum at test temperatures between 85 and 90F (29.4 and 32.2C) (Snyder, 1968a). These increases of 35 to 40F (19.4 to 22.2C) approximated the levels typical of a nuclear reactor discharge plume in the Columbia River. The results indicated temperature increases of 35 to 40F (19.4 to 22.2C) are lethal when the river is at 50F (10C), that increases of 25 to 30F (13.8 to 16.6C)are lethal at a river temperature of 60F (15.6C), and that increases of 15 to 20F (8.3 to 11.1C) are probably lethal when the river is at 70F (21.1C).

E. Adults

There are few investigations on the thermal relationships of adult chum; however, studies on Sand Creek, Oregon, showed that the peak periods of migration over a three-year period occurred at temperatures from 42.5 to 52F (5.8 to 11.1C) (Sumner, 1952).

Research Needs

Further investigations are needed to better understand the impact of thermal stress on Pacific salmon and their environment. The following topics represent the most urgent research needs and have been developed by the Federal Water Pollution Control Administration, the Bureau of Commercial Fisheries and the Atomic Energy Commission as a part of the Columbia River Thermal Effects Study.

Adult Salmonids

1. Timing of upstream migration as related to temperature.
2. Location of fish in stream cross section or water column during upstream migration.
3. The incidence of infectious disease as a function of temperature.
4. Viability of gametes in relation to temperature experience of fish.
5. The occurrence and significance of the gas-bubble disease in relation to temperature.
6. Ability of fish to detect and avoid heated effluents and define conditions necessary to cause a thermal block.
7. Optimum temperature range for egg survival.

Juvenile Salmonids

1. Ability of young salmonids to survive, grow and migrate as a function of different temperature regimes.

2. Supersaturation of nitrogen as a function of behavior, tolerance and survival.
3. Distribution of resident or migrating young salmonids in river cross section.
4. Ability of young salmonids to detect and avoid unfavorable temperature zones.
5. Ability of fingerlings to tolerate and survive a range of temperatures.
6. Physiological adaptation to salt water in relation to temperature experience.
7. Effect of temperature on toxicity and synergism of pollutants.

Other important areas where research is needed include the following topics:

1. The relation of flow regulation and existing thermal effluents to fish temperature requirements.
2. The effect of temperature on fish food organisms.
3. The effect of a temperature-induced change in food organisms on salmon.
4. The effects of temperature change on the predation of downstream migrants.
5. The effects of temperature on sensory perception.
6. A determination of energy needs to assess different performances under natural and thermally stressed conditions.
7. The point at which a thermal load becomes a stress.

8. The protection of salmon from high water temperatures during certain seasons of the year compounded by low flows caused by dams.
9. The protection of fish from thermal plant effluents by disposing of the waste heat by means other than the river.
10. The effects of thermal shock on the eggs and young of salmon when passing through cooling condenser tubes.
11. An autopsy technique for thermal death.
12. The biochemical effects of temperature.
13. The histopathological effects of temperature.
14. The possible adaptation of salmon to higher temperatures.
15. The thermal tolerance differences between different species of salmon during development.

Federal Government Sponsored Research

Agencies currently supporting temperature-related research projects relative to salmon include the Federal Water Pollution Control Administration, Bureau of Commercial Fisheries, Bureau of Sport Fisheries and Wildlife, Atomic Energy Commission, Office of Water Resources Research, and the Army Corps of Engineers.

Three of these agencies, the Federal Water Pollution Control Administration, the Bureau of Commercial Fisheries and the Atomic Energy Commission have formed the Columbia River Thermal Effects Study. Their cooperative efforts are designed to provide a scientific basis for the evaluation of the temperature regime of the mainstem Columbia River and its effects on the river's ecology, particularly upon the economically important anadromous and resident fish.

Information about the following projects came from: 1) the 1967 edition of the U. S. Department of the Interior Water Resources Catalog; 2) the Smithsonian Institution Science Information Exchange with permission of the principal investigators; and 3) those agencies making up the Columbia River Thermal Effects Study.

Supporting Agency: Federal Water Pollution Control Administration

L. S. Smith, University of Washington, is heading the project "Responses of Fish to Environmental Stress." Physiological tests will attempt to determine the effect of thermal, osmotic, pollution and capture stresses.

G. R. Bouck, Pacific Northwest Water Laboratory, Corvallis, Oregon, is directing two projects as part of the Columbia River Thermal Effects Study. "Tissue Enzyme Studies" will provide a biochemical basis for establishing thermal tolerance limits. "Simulation of Adult Salmon Migration Through Elevated Temperatures and the Effects on Gametes and Progeny" will assess the potential effects of migration in cool and heated Columbia River water.

Supporting Agency: U. S. Bureau of Commercial Fisheries

The Bureau and the University of Washington, R. L. Burgner, principal investigator, are conducting a study to determine the optimum escapement levels of Alaskan sockeye salmon. The investigation, "Study of Red Salmon in the Nushgak District," regularly obtains physical and chemical data to help determine spawning area requirements.

The Bureau has three projects in Auke Bay, Alaska. "Pink Salmon Investigations--Freshwater Ecology," headed by W. R. Heard, will study temperature, dissolved oxygen, water flow and siltation in relation to mortality rates in spawning beds.

"Pink Salmon Investigations--Early Sea Life of Salmon," led by T. W. Martin, will include investigations of the relation of sea temperatures to salmon fry survival, studies of the effects of water temperature on salmon fry raised in controlled temperature saltwater, and an investigation of the life histories of salmon parasites.

"Chum Salmon Investigation", headed by C. R. Mattson, will relate estuarine environmental factors such as temperature, salinity, current and turbidity to juvenile pink and chum salmon abundance and behavior.

H. L. Raymonds of the Bureau's Fish Passage Research Program in Seattle is directing two pertinent studies. "Juvenile Migration Rates" will determine the effect of new dams and reservoirs on the Columbia and Snake Rivers on the survival of downstream migrating chinook salmon. "Adult Migration Rates" will use sonic tagging to predict possible changes in future populations and migration timing of salmon due to dams and reservoirs on the Columbia River.

The Fish Passage Research Program and Oregon State University, L. A. Fulton, investigator, are analyzing climatological, hydrological and physical data from the Columbia and Snake Rivers to predict future environments in order to protect salmon runs. The project, "Prediction of Environment in Rivers and Reservoirs," will also study the possibility of lowering the temperatures in the main stems of these rivers by tapping the cool waters at the bottom of the lakes and reservoirs formed by the dams.

The following Columbia River Thermal Effects Study projects are being conducted at the Bureau's Seattle Montlake Biological Laboratory or at the Water Temperature Laboratory in Prescott, Oregon.

"Adult Salmon Behavior in Rivers" is a continuing project led by J. H. Johnson. It is designed to contribute to a sound assessment of the effects of reservoirs and dams on anadromous fish runs, specifically on adult salmonids returning to Columbia River system spawning areas. The basic research tool is the sonic fish tag.

"Adult Fish Passage," headed by C. R. Weaver, will determine how migrating salmonids respond to differences in water temperature. The results will indicate how altered temperatures could influence the migration rates of adult salmonids and affect fish passage at dams.

A. Novotny is the project leader of "Prediction of Environmental Conditions in John Day Reservoir, Columbia River." An intensive study of McNary Reservoir is being used to predict physical, chemical and biological environments in John Day Reservoir. This information will be pertinent and relative to any environmental conflicts (with respect to salmonids) which might arise from the creation of this new reservoir.

T. Blahm is heading three projects on thermal tolerance. "Thermal Shock of Juvenile Salmonids" will determine the tolerance and survival of juvenile salmonids subjected to sharp temperature increases. "Thermal Tolerance of Juvenile Salmonids" will determine the thermal tolerance and survival of juvenile salmonids subjected to a range of temperatures. "Thermal Tolerance of Non-Salmonids" will determine the survival and tolerance of non-salmonids subjected to a range of temperatures.

Two projects are being led by R. McConnell. "Thermal Tolerance of Juvenile Salmonids in Relation to Nitrogen Saturation" will determine how supersaturation of nitrogen gas changes the behavior, tolerance and survival of migrating juvenile salmonids. "'On Site' Timing of Movement of Juvenile Fish at Prescott, Oregon" will establish the timing of movement of juvenile salmonids and juvenile and adult non-salmonids. Both the lateral and horizontal movement of the fish at index sites above and below proposed Lower Columbia River thermal electric plants will be determined.

S. Clark is the project leader of two studies on the Lower Columbia River. "Limnological Survey of the Lower Columbia River" will determine the physical, chemical and biological environment of the Columbia River prior to the installation of thermal electric plants. "Thermal Tolerance of Zooplankton of the Lower Columbia River" will establish the thermal tolerance of the most common species of zooplankton.

The project, "Physiological Effect of Temperature Increase on Anadromous Fish of the Lower Columbia River" will establish the physiological effect of short and long term "heat death" on salmonids and non-salmonids. Temperature effects on the reproductive capacity of smelt, shad and sturgeon will be emphasized.

Supporting Agency: U. S. Bureau of Sport Fisheries and Wildlife

R. R. Rucker of the Bureau's Western Fish Disease Laboratory, Seattle, is heading the project, "Biochemical Changes in Fish Diseases: Interferon Production in Chinook, Sockeye, and IPN Virus Infections of Fish." The role of interferon production in the viral diseases of fish is largely unknown. Temperature dependency of interferon production will be correlated with water temperature and ease of infection. Work in this area has been postponed due to curtailment of funds.

R. E. Burrows of the Bureau's Salmon Cultural Laboratory, Longview, Washington, is leading the project, "Definition of Fingerling Characteristics Necessary for Maximum Adult Survival." This study will determine the optimum environmental conditions for chinook fingerling rearing. One group of fall chinook fingerlings will be raised at 53F (11.7C) for five months and compared to a similar group raised at temperatures ranging from 37F (2.8C) to 50F (10C). Both groups will be released at the same time. The return of the adults will determine if larger, disease-free fish at the time of release will produce a greater return of adult fish.

Supporting Agency: Atomic Energy Commission

R. E. Nakatani, Battelle Memorial Institute, Richland, Washington, will investigate the basic nature of temperature effects in aquatic organisms in the project, "Biochemical and Molecular Effects of Temperature in Aquatic Organisms." The fish in these studies will be acclimated to different temperatures and the temperature-induced changes will be quantitated with the use of biochemical, histological, physiological and electron microscopical techniques.

The following projects of the Columbia River Thermal Effects Study are also being conducted at the Pacific Northwest Laboratory, Battelle Memorial Institute.

M. P. Fujihara is the principal investigator of two of these studies. "Gas-Bubble Disease on Young Salmonids" will identify the interactions of temperature and supersaturated gases in the potential development of "gas-bubble disease" by downstream-migrating juvenile salmonids. The probability of thermal mixing zones inducing "gas-bubble disease" in fish acclimated to supersaturated Columbia River conditions will be assessed. This study will also explore the feasibility of detecting the various stages of "gas-bubble disease" in adult salmonids by physiological differences in blood serum using gas chromatographic techniques. "Effects of Temperature on C. columnaris, Dermocystidium salmonis and A. salmonicida Fish Disease" will investigate the significance of water temperature on these diseases in the Hanford-Columbia River environment.

P. A. Olson is the principal investigator of "Effects of Fluctuating Temperatures on Survival and Growth of Juvenile Chinook Salmon." This project will determine to what extent water temperature variations can occur around a reference mean value and still be acceptable for young salmon development.

"Hanford Chinook Salmon Population Studies," with D. G. Watson as principal investigator, will evaluate the effects of reactor effluents on fall chinook salmon spawning in the Columbia River near Hanford. This project will add to knowledge of migration timing as related to temperature in addition to supplementing Columbia River salmon population investigations.

Two projects are under the principal investigation of C. D. Becker. "Effect of Thermal Shock from Effluent Discharge on Young Chinooks" will evaluate the effect of thermal shock upon juvenile chinook salmon passing through heated effluents, discharging from mid-stream plumes or seeping from shoreline retention basins in the Hanford section. "Relationships of Thermal Discharge to Food and Feeding of Juvenile Chinook Salmon" has two objectives: 1) To evaluate the food composition and feeding activity of young chinook salmon (0-age group) during the spring period of seaward migration, and 2) To determine if the heated reactor effluents, through direct effects and indirect interactions, influence the welfare of the fish in the Hanford area.

C. C. Coutant is the principal investigator of three projects. "Performance of Thermally Shocked Young Salmon" will assess the effects of sublethal doses of potentially lethal temperatures, and chronic exposures to temperature outside "optimum" thermal zones, on the performance of downstream migrant salmonids. "Sonic tracking of Adult Salmonids" will investigate the movement of sonic-tagged adult salmonids near Hanford reactor plumes and the Hanford reach of the Columbia River. This project will contribute to a better understanding of the ability of adult fish to detect and avoid heated plumes and also help to define conditions necessary for a thermal block. "Temperature Tolerances of Adult Salmon" will determine in the laboratory the median death times of jack salmon exposed to lethal temperature. This project will contribute to studies on the water quality requirements and tolerances of adult salmonids.

Supporting Agency: Office of Water Resources Research

Dam construction and downstream water temperatures are being studied by R. E. Nece of the University of Washington. One application of the project, "Effect of Dam Construction on Downstream Water Temperature," will relate the building of more dams to changes in the ecology of fish resources.

Supporting Agency: U. S. Army Corps of Engineers

Fish collection facilities at high water storage projects where waters of different temperatures are released through turbines are being studied by J. R. Gauley, Fisheries Engineering Research Laboratory, North Bonneville, Washington. Preliminary results of the study, "Migratory Responses of Adult Salmonids to Water Temperature," indicated that chinook, coho and sockeye salmon showed no preference between existing river water temperature and water heated 3F (1.7C) above this temperature. However, some fish showed a preference for river water temperature when given a choice between it and water 7F (3.9C) warmer.

The Oregon Fish Commission Laboratory has two projects under the leadership of L. Korn. "Evaluation of Anadromous Fish Passage Facilities at Cougar Dam, South Fork McKenzie River, Oregon" will determine the effect of the dam on survival, growth and passage of juvenile salmonids. This project will also monitor the environment for changes. "Evaluation of Anadromous Fish Passage Facilities at Fall Creek Dam, Big Fall Creek, Oregon" will determine the effect of Fall Creek Dam on juvenile salmon passage and will also monitor the environment for pertinent changes.

Bibliography

Alderdice, D. F., (1963), "Some Effects of Simultaneous Variation in Salinity, Temperature and Dissolved Oxygen on the Resistance of Young Coho Salmon to a Toxic Substance," Journal of Fisheries Research Board of Canada, 20, 525-550.

Ali, M. A., (1960), "The Effect of Temperature on the Juvenile Sockeye Salmon Retina," Canadian Journal of Zoology, 38, 169-171.

Allen, G. H., (1959), "Behavior of Chinook and Silver Salmon," Ecology, 40, 108-113.

Baggerman, B., (1959), "The Role of External Factors and Hormones in Migration of Sticklebacks and Juvenile Salmon," Comparative Endocrinology, 16, 24-37.

Borg, A. F., (1948), "Studies on Myxobacteria Associated with Disease in Salmonid Fishes," Ph. D. Thesis, University of Washington.

Brett, J. R., (1952), "Temperature Tolerance in Young Pacific Salmon, Genus Oncorhynchus," Journal of Fisheries Research Board of Canada, 9, 265-323.

Brett, J. R., (1956), "Some Principles in the Thermal Requirements of Fishes," Quarterly Review of Biology, 31, 75-87.

Brett, J. R., (1957), "Salmon Research and Hydroelectric Power Development," Journal of Fisheries Research Board of Canada, 114.

Brett, J. R., (1958), "Implications and Assessments of Environmental Stress," The Investigation of Fish Power Problems: H. R. MacMillan Lectures in Fisheries, University of British Columbia, 69-83.

Brett, J. R., (1960), "Thermal Requirements of Fish - - Three Decades of Study, 1940-1970," Biological Problems in Water Pollution, Second Seminar, Trans. Robert A. Taft Sanitary Engineering Center, Technical Report W60-3, 110-117.

Brett, J. R., (1964), "The Respiratory Metabolism and Swimming Performance of Young Sockeye Salmon," Journal of Fisheries Research Board of Canada, 21, 1183-1226.

Brett, J. R., (1967), "Swimming Performance of Sockeye Salmon (Oncorhynchus nerka) in Relation to Fatigue Time and Temperature," Journal of Fisheries Research Board of Canada, 24, 1731, 1741.

Brett, J. R., and Alderdice, D. F., (1958), "The Resistance of Cultured Young Chum and Sockeye Salmon to Temperatures Below 0°C," Journal of Fisheries Research Board of Canada, 15, 805-813.

Brett, J. R., Hollands, M., and Alderdice, D. F., (1958), "The Effect of Temperature On the Cruising Speed of Young Sockeye and Coho Salmon," Journal of Fisheries Research Board of Canada, 15, 587-605.

Briggs, J. C., (1953), "The Behavior and Reproduction of Salmonid Fishes in a Small Coastal Stream," California Department of Fish and Game, Fisheries Bulletin, 94.

Burrows, R. E., (1954), "Effect of Controlled Temperatures on Salmon Eggs," Presented at the Fish Cultural Conference, Seattle, Washington, December 2-3, 1954, 46.

Burrows, R. E., (1960), "Holding Ponds for Adult Salmon," U. S. Fish and Wildlife Service Special Scientific Report--Fisheries. No. 357.

Burrows, R. E., (1963), "Water Temperature Requirements for Maximum Productivity of Salmon," Water Temperature--Influences, Effects, and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Water Laboratory, Public Health Service, U. S. Department of Health, Education, and Welfare (reissued April 1967, FWPCA)

Chapman, W. M., (1941), "Observations on the Migration of Salmonid Fishes in the Upper Columbia River," Copeia, 4, 240-242.

Colgrove, D. J., and Wood, J. W., (1966), "Occurrence and Control of Chondrococcus columnaris as Related to Fraser River Sockeye Salmon," International Pacific Salmon Fisheries Commission Progress Report No. 15.

Combs, B. D., (1965), "Effect of Temperature on the Development of Salmon Eggs," Progressive Fisheries Culture, 27, 134-137.

Combs, B. D., and Burrows, R. E., (1957), "Threshold Temperatures for the Normal Development of Chinook Salmon Eggs," Progressive Fisheries Culture, 19, 3-6.

Combs, B. D., Burrows, R. E., and Bigej, R. E., (1959), "The Effect of Controlled Light on the Maturation of Adult Blueback Salmon," Progressive Fisheries Culture, 21, 63-69.

Coutant, C. C., (1968), "Behavior of Adult Salmon and Steelhead Trout Migrating Past Hanford Thermal Discharges," Biological Effects of Thermal Discharges," Annual Progress Report for 1967, Reprinted from USAEC Research and Development Report No. BNWL-714, 8-11.

Coutant, C. C., and Dean, J. M., (1967), "Temperature Tolerances of Young Chinook Salmon with Differing Developmental Temperatures," Battelle Northwest Laboratory-SA-1487 (Presented at the Pacific Northwest Pollution Control Association's Annual Meeting at Yakima, Washington, Oct. 27, 1967).

Dahlberg, M. L., Shumway, D. L., Doudoroff, P., (1968), "Influence of Dissolved Oxygen and Carbon Dioxide on Swimming Performance of Largemouth Bass and Coho Salmon," *Journal of Fisheries Research Board of Canada*, *25*, 49-70.

Davis, H. S., (1961), *Culture and Diseases of Game Fishes*, University Of California Press, Los Angeles.

Davis, G. E., Foster, J., Warren, C. E., and Doudoroff, P., (1963), "The Influence of Oxygen Concentration on the Swimming Performance of Juvenile Pacific Salmon at Various Temperatures," American Fisheries Society, *Transactions*, *92*, 11-124.

Davis, W. S., and Snyder, G. R., (1967), "Aspects of Thermal Pollution That Endanger Salmonid Fish in the Columbia River," U. S. Bureau of Commercial Fisheries, Seattle, Washington.

Dean, J. M., and Coutant, C. C., (1968), "Lethal Temperature Relations of Juvenile Columbia River Chinook Salmon," *Biological Effects of Thermal Discharges*, Annual Progress Report for 1967. Reprinted from USAEC Research and Development Report No. BNWL-714 (Battelle Memorial Institute, Richland Washington).

Delong, D. C., Halver, J. E., and Mertz, E. T., (1958), "Nutrition of Salmonid Fishes, VI. Protein Requirements of Chinook Salmon at Two Water Temperatures," *Journal of Nutrition*, *65*, 589-599.

Delong, D. C., Halver, J. E., and Mertz, E. T., (1962), "Nutrition of Salmonid Fishes, X. Quantitative Threonine Requirements of Chinook Salmon at Two Water Temperatures," *Journal of Nutrition*, *76*, 174-178.

Donaldson, J. R., (1954), "Effect of Variation of Temperatures on Eggs," Northwest Fish Cultural Conference, Seattle, Washington, Dec. 2-3, 1954, 47.

Donaldson, L. R., and Foster, F. J., (1941), "Experimental Study of the Effect of Various Water Temperatures on the Growth, Food-Utilization and Mortality Rate of Fingerling Sockeye Salmon," *American Fisheries Society*, *Transactions*, *70*, 339-346.

Eaton, M. F., (1967), "Frazer Lake Sockeye Investigations," Alaska Department of Fish and Game, Informational Leaflet No. 119.

Ferguson, R. G., (1958), "The Preferred Temperature of Fish and Their Mid-Summer Distribution in Temperate Lakes and Streams," Journal of Fisheries Research Board of Canada, 15, 607-624.

Fish, F. F., (1944), "The Retention of Adult Salmon with Particular Reference to the Grand Coulee Fish Salvage Program," U.S. Fish and Wildlife Service Special Scientific Report No. 27.

Fish, F. F., (1948), "The Return of Blueback Salmon to the Columbia River," Scientific Monthly, 66, 283-292.

Fish, F. F., and Burrows, R. E., (1939), "Notes on the Effect of Low Temperatures on Eyed Eggs," Progressive Fisheries Culture, 45, 28-31.

Fish, F. R., and Rucker, R. R., (1943), "Columnaris as a Disease of Freshwater Fishes," American Fisheries Society, Transactions, 73, 32-36.

Fisher, K. C., and Scott, G. W., (1942), "On the Physiological Mechanisms of Temperature 'Selection' by Fish," The Collecting Net, 17, 48.

Fisheries Research Board of Canada,(1962), Annual Report of Fisheries Research Board of Canada, 1961-1962.

Foerster, R. E., (1937), "The Relation of Temperature to the Seaward Migration of Young Sockeye Salmon (Oncorhynchus nerka)." Journal of Biology Board of Canada, 3, 421-438.

French, R. R., and Wahle, R. J., (1959), "Biology of Chinook and Blueback Salmon and Steelhead in the Wenatchee River System," U.S. Fish and Wildlife Service Special Scientific Report--Fisheries, No. 304.

Fry, F. E. J., (1951), "Some Temperature Relations of Fish," Federation Proceedings, 10, 46.

Fujihara, M. P., (1967), "Immune Response of Salmonids and Exposure of River Fishes to Chondrococcus columnaris," Pacific Northwest Annual Report for 1966 to the USAEC Division of Biology and Medicine, Vol. 1 Biological Sciences, BNWL-480 (Battelle Memorial Institute, Richland, Washington), 183-185.

Fujihara, M. P., (1968), "Columnaris Exposure and Antibody Production in Seaward and Upstream Migrant Sockeye Salmon," Biological Effects of Thermal Discharges, Annual Progress Report for 1967, Reprinted from USAEC Research and Development Report No. BNWL-714 (Battelle Memorial Institute, Richland, Washington), 14-19.

Fujihara, M. P., and Olson, P. A., (1962), "Incidence and Virulence of Columnaris," Hanford Biology Research Annual Report for 1961, HW-72500 (General Electric Company, Richland, Washington), 151-155.

Fujihara, M. P., Olson, P. A., and Foster, R. F., (1960), "Mutation and Temperature Effects in *C. columnaris*," Hanford Biology Research Annual Report for 1959, HW-65500 (General Electric Company, Richland, Washington), 188-193.

Gangmark, H. A., and Broad, R. D., (1955), "Experimental Hatching of King Salmon in Mill Creek, a Tributary of the Sacramento River," California Fish and Game, *41*, 233-242.

Garnjobst, L., (1945), "*Cytophaga columnaris* (Davis) in Pure Culture: A Myxobacterium Pathogenic to Fish," *Journal of Bacteriology*, *49*, 113-128.

Gribanov, V. I., (1962), "The Coho Salmon (*Oncorhynchus kisutch* Walbaum)- A Biological Sketch," (Transl. from Russian), Fisheries Research Board of Canada--Transl. Series No. 370.

Hartman, W. L., Heard, W. R., and Drucker, B., (1967), "Migratory Behavior of Sockeye Salmon Fry and Smolts," *Journal of Fisheries Research Board of Canada*, *24*, 2069-2099,

Hoar, W. S., (1951), "The Behavior of Chum, Pink, and Coho Salmon in Relation to Their Seaward Migration," *Journal of Fisheries Research Board of Canada*, *8*, 241-263.

Hoar, W. S., (1958), "The Evolution of Migratory Behavior Among Juvenile Salmon of the Genus *Oncorhynchus*," *Journal of Fisheries Research Board of Canada*, *15*, 391-428.

Int. Pacific Salmon Fisheries Commission, (1962), Report of the International Pacific Salmon Fisheries Commission for the year 1961.

Johnson, H. E., and Brice, R. F., (1952), "Observations on Columnaris in Salmon and Trout," *Progressive Fisheries Culture*, *14*, 104-109.

Johnson, H. E., and Brice, R. F., (1953), "Effects of Transportation of Green Eggs, and of Water Temperature During Incubation, on the Mortality of Chinook Salmon," *Progressive Fisheries Culture*, *15*, 104-108.

Johnson, T. S., Conte, F. P., and Nakatani, R. E., (1967), "The Effects of Temperature and X-Irradiation on the Intestinal Epithelial Cells of Juvenile Silver Salmon," Pacific Northwest Laboratory Annual Report for 1966 to the USAEC Division of Biology and Medicine, Vol. 1 Biological Sciences BNWL-480, Battelle Mem. Inst.

Junge, C. O., Jr., and Phinney, L. A., (1963), "Factors Influencing the Return of Fall Chinook Salmon (Oncorhynchus tshawytscha) to Spring Creek Hatchery," U.S. Fish and Wildlife Service Special Scientific Report--Fisheries, No. 445.

Kanid'ev, A. V., and Frolenko, L. A., (1966), "The Rearing of Chum Salmon (Oncorhynchus keta) in Hatcheries at Low Water Temperatures," (Transl. from Russian), Ref. ZH Biol. No. 21185.

Keenleyside, M. H. A., and Hoar, W. S., (1954), "Effects of temperature on the Responses of Young Salmon to Water Currents," Behavior, 7, 77-87.

Krogius, F. V., (1959), "The Relation of the Up-River Migration of Sockeye Salmon and the Seaward Migration of their Young to the Daily Cycle of Water Temperature, pH, and Content of Dissolved Gases," (Transl. from Russian), Fisheries Research Board of Canada--Transl. Series No. 169.

Krogius, F. V., and Krokhim, (1958), "The Run of Sockeye and the Daily Temperature Rhythm in the Paratunka River," (Transl. from Russian), Fisheries Research Board of Canada, Transl. Series No. 197.

Krokhim, E. M., (1961), "Spawning Grounds of Sockeye Salmon (Oncorhynchus nerka Walbaum)," (A Review of their Geomorphology, Temperature Conditions and Hydrochemistry,) (Transl. from Russian) Fisheries Research Board of Canada--Transl. Series No. 344.

Kubo, T., (1950), "A Preliminary Report of the Study of the Groups of Oncorhynchus keta (Walbaum) (dog salmon) and the Number of Their Segments," Bulletin of Faculty Fisheries Hokkaido University, 1, 1-11.

Leitritz, E., (1962), "Trout and Salmon Culture (Hatchery Methods)," California Department of Fish and Game, Fish Bulletin, 107.

Major, R. L., and Mighell, J. L., (1966), "Influence of Rocky Reach Dam and the Temperature of the Okanogan River on the Upstream Migration of Sockeye Salmon," U.S. Fish and Wildlife Service, Fish Bulletin, 66, 131-147.

Mazuranich, J. J., and Nielson, W. E., (1959), "White-Spot Disease of Salmon Fry," Progressive Fish-Cult., 21, 172-176.

McNeil, W. J., (1966), "Effect of the Spawning Bed Environment on Reproduction of Pink and Chum Salmon," U.S. Fish and Wildlife Service, Fisheries Bulletin, 65, 495-523.

Moffett, J. W., (1949), "The First Four Years of King Salmon Maintenance Below Shasta Dam, Sacramento River, California," Calif. Game and Fish, 35, 77-107.

Olson, P. A., (1967a), "Effect of Elevated Temperature on Mortality of Chinook Salmon," Abstract, Battelle Northwest Laboratory--SA-1478A (Presented at the Pacific Northwest Pollution Control Association's Annual Meeting at Yakima, Washington, Oct. 27, 1967).

Olson, P. A., (1967b), "Reactor Effluent Monitoring: Comparison of Puget Sound and Priest Rapids Chinook Salmon," Pacific Northwest Laboratory Annual Report for 1966 to the USAEC Division of Biology and Medicine, Vol. 1 Biological Sciences, BNWL-480, 180-181.

Olson, P. A., and Foster, R. F., (1957), "Temperature Tolerance of Eggs and Young of Columbia River Chinook Salmon," American Fish. Soc. Trans., 85, 203-207.

Olson, P. A., and Fujihara, M. P., (1963), "Incidence and Virulence of Columnaris--II," Hanford Biology Research Annual Report for 1962, HW-76000 (General Electric Company, Richland, Washington,) 223-226.

Olson, P. A., and Nakatani, R. E., (1968), "Effect of Elevated Temperatures on Mortality and Growth of Young Chinook Salmon," Biological Effects of Thermal Discharges, Annual Progress Report for 1967, 1-3.

Ordal, E. J., and Pacha, R. E., (1963), "The Effects of Temperature on Disease in Fish," Water Temperature--Influences, Effects and Control, Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Pacific Northwest Water Laboratory.

Pacific Northwest Laboratories, (1967), "Effects of Elevated Temperatures on Aquatic Organisms, Appendix D," Final Report on Nuclear Power Plant Siting in the Pacific Northwest for the Bonneville Power Administration, Battelle Memorial Institute.

Parisot, T. J., and Pelnar, J., (1962), "An Interim Report on Sacramento River Chinook Disease: A Viruslike Disease of Chinook Salmon," Progressive Fish-Cult., 24, 51-55.

Parker, R. R., and Vincent, P. E., (1955), Progress Report on Research Studies at the Kitoi Bay Research Station, Alaska Department of Fisheries Annual Report for 1955, 25-67.

Pauley, G. B., and Nakatani, R. E., (1967), "Histopathology of 'Gas-Bubble' Disease in Salmon Fingerlings," Journal of Fisheries Research Board of Canada, 24, 867-871.

Pritchard, A. L., (1936), "Factors Influencing the Upstream Spawning Migration of the Pink Salmon, Oncorhynchus gorbuscha (Walbaum)," Journal of Biology Board of Canada, 2, 383-389.

Prichard, A. L., (1944), "Physical Characteristics and Behavior of Pink Salmon Fry at McClinton Creek, B. C.," Journal of Fisheries Research Board of Canada, 6, 217-227.

Progressive Fish-Culturist, (1958), "Light as a Factor in Accelerating the Spawning of Blueback Salmon, " Prog. Fish-Cult., 20, 57.

Reingold, M., (1968), "Water Temperature Affects the Ripening of Adult Fall Chinook Salmon and Steelhead," Prog. Fish-Cult., 30, 41-42.

Robins, L. G., (1964), "The Effect of Columnaris in Mature Sockeye and Pink Salmon on the Viability of their Eggs and Sperm," Prog. Fish-Cult., 26, 186-187.

Rockwell, J., Jr., (1956), "Some Effects of Sea Water and Temperature on the Embryos of the Pacific Salmon, Oncorhynchus gorbuscha (Walbaum)," Dissertation .

Ross, A. J., Pelnar, J., and Rucker, R. R., (1960),"A Virus-Like Disease of Chinook Salmon," American Fisheries Soc., Trans., 89, 160-163.

Royal, L. A., (1953), "The Effects of Regulatory Selectivity on the Productivity of the Frazer River Sockeye," Canadian Fish-Cult., 14, 1-12.

Royce, W. F., (1959), "On the Possibilities of Improving Salmon Spawning Area," 24th North American Wildlife Conference, Trans., March 2-4, 1959, 356-366.

Rucker, R. R., (1937), "The Effect of Temperature on the Growth of the Embryos of Oncorhynchus nerka (Walbaum), " M.S. Thesis, University of Washington.

Rucker, R. R., Earp, B. J., and Ordal, E. J., (1953), "Infectious Diseases of Pacific Salmon," American Fish. Soc, Trans., 83.

Seymour, A. H., (1954), "Effect of High Constant Temperatures Upon the Mortality and Growth of Chinook Salmon Eggs, Fry, and Fingerlings," Northwest Fish Cultural Conference, Seattle, Wash., Dec. 2-3, 1954, 45.

Seymour, A. H., (1959), "Effects of Temperature Upon the Formation of Vertebrae and Fin Rays in Young Chinook Salmon, " Amer. Fish. Soc., Trans., 88, 58-69.

Shapovalov, L., and Taft, A. C., (1954), "The Life Histories of the Steelhead Rainbow Trout (Salmo gairdneri gairdneri) and Silver Salmon (Oncorhynchus kisutch) with Special Reference to Waddel Creek, California, and Recommendations Regarding Their Management," Calif. Dept. Fish and Game, Fish Bulletin, 98.

Shaw, P. A., (1946), "Oxygen Consumption of Trout and Salmon, " Calif. Fish and Game, 32, 3-12.

Shelbourn, J. E., (1966), "Influence of Temperature, Salinity and Photoperiod on the Aggregations of Chum Salmon Fry (Oncorhynchus keta)," Journal of Fisheries Research Board of Canada, 23, 293-304.

Sheridan, W. L., (1960), "Relation of Stream Temperatures to Timing of Pink Salmon Escapements in Southeast Alaska," Symposium on Pink Salmon, H. R. MacMillan Lectures in Fisheries, University of British Columbia, Vancouver, Canada, 87-102.

Sheridan, W. L., (1961), "Temperature Relationships in a Pink Salmon Stream in Alaska,"Ecology, 42, 91-98.

Slater, D. W., (1963), "Winter-Run Chinook Salmon in the Sacramento River, California" with notes on water temperature requirements at spawning," U.S. Fish and Wildlife Service Special Scientific Report--Fisheries, No. 461.

Snyder, G. R., (1968a), "Thermal Plants, Thermal Pollution, and Fish--the Problem in the Columbia River and the Pacific Northwest," Bureau of Comm. Fish., Biol. Lab., Seattle.

Snyder, G. R., (1968b), "Nuclear Power Versus Fisheries," Bur. Comm. Fish., Seattle, Presented at Annual Directors' Meeting of Izaak Walton League, Portland Oregon, Feb. 17, 1968.

Snyder, G. R., Bjorn, T. C., Greenland, D. C., Hasselman, R. W., Monan, G. E., Novotny, A. J., and Phillips, R. W., (1966), "Temperature Standards Conductive to Optimum Production of Salmonids in Columbia Basin Waterways," Preliminary Report, U.S. Bureau of Comm. Fish., Seattle, Washington.

Sumner, F. H., (1952), "Migrations of Salmonids in Sand Creek, Oregon," Amer. Fish. Soc., Trans., 82, 139-150.

Varma, C. P., (1950), "Study of the Effect of Sudden Temperature Changes and Fasting Upon the Survival of Trout and Salmon Fingerlings," M.S. Thesis, University of Washington.

Vernon, E. H., (1958), "An Examination of Factors Affecting the Abundance of Pink Salmon in the Fraser River, B. C., " Progress Report Int. Pacific Salmon Fisheries Comm. for 1958.

Ward, H. B., (1921), "Some of the Factors Controlling the Migration and Spawning of the Alaska Red Salmon," Ecology, 2, 235-254.

Washington State Department of Fisheries, (1960), "Experimental Studies on the Survival of the Early Stages of Chinook Salmon after Varying Exposures to Upper Lethal Temperatures," Progress Report on Fish. Eng. Res. Program, North Pacific Division, Corps of Engineers, U.S. Army, 143-149.

Westgard, R. L., (1964), "Physical and Biological Aspects of Gas-Bubble Disease in Impounded Adult Chinook Salmon at McNary Spawning Channel," Amer. Fish. Soc., Trans., 93, 306-309.

Wickett, W. P., (1960), "Environmental Variability and Reproduction Potentials of Pink Salmon in British Columbia," Symposium on Pink Salmon, H. R. MacMillan Lectures in Fisheries, University of British Columbia, Vancouver, B. C., 73-86.

Withler, F. C., (1952), "Estimation of the Size of the Sockeye Smolt Run, Babine Lake," (1951), Fish. Res. Board of Canada, Pacific Coast Station Progress Report No. 91, 17-19.